Development of a Group Built Coupled Physical – Socio-Economic Modelling Framework for Soil Salinity Management in Agricultural Watersheds in Developing Countries

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ABSTRACT

Stakeholder involvement in environmental modeling has gained considerable importance over the past twenty years. However, many water resource planning and management frameworks encounter significant challenges when trying to develop tools that do not require significant funding, time, or expertise and that facilitate stakeholder engagement in developing countries. This study aims to address such challenges by developing a stepwise participatory modeling framework to link physically-based models with stakeholder-assisted socio-economic models in the context of developing countries, using the Rechna Doab region of Pakistan as a case study area.

Participatory system dynamics models (PSDM) were developed under constraints of limited expertise and financial and time resources by contacting potential stakeholder (e.g. local farmers, experts, government officials) and representing their views and policy options in the form of qualitative causal loop diagrams (CLDs). A holistic qualitative model of the watershed system was created by merging these individual causal loop diagrams. Meaningfully including stakeholder contributions in the modeling process helps incorporate the ideas and knowledge of local key stakeholders, integrates physical and socio-economic components within a watershed or sub-watershed, and improves model boundaries and completeness by ensuring that all relevant issues and views are addressed.

The key physical and socio-economic processes were identified from the stakeholder-built CLDs. The socio-economic components were modeled through distributed submodules in a Group-Built System Dynamics Model (GBSDM). The distributed submodules represented canal seepage, surface storage, irrigation application and distribution, groundwater extraction, effective rainfall and runoff, irrigation efficiency improvement, agriculture water demand, and farm income. Feedbacks between the distributed submodules describe the interactions between them and allow for simulation of the behavior of the whole system at the watershed scale. The recommended structural and behavior validity tests were then employed to test and build confidence in the modeling system.

The physical components of the CLDs were modeled through the Spatial Agro-Hydro-Salinity Model (SAHYSMOD), a distributed model that simulates groundwater changes as well as salt and water movement within the crop root zone at the watershed scale. The model was calibrated (1983-1988) and validated (1998-2003) over two five-year periods through comparison of observed and simulated groundwater levels. The model simulated groundwater elevation

accurately with observed R^2 values of 0.906 and 0.925, Nash–Sutcliffe model efficiencies of 0.812 and 0.873, and mean errors of 0.436 and 0.486 for the calibration and validation periods, respectively. Uncertainty and sensitivity analyses performed on the model using Generalised Likelihood Uncertainty Estimation (GLUE) estimated that 70% of the observed data falls within the 95% and 5% uncertainty bounds. These results indicate a good approximation of selected calibrating parameter ranges. Furthermore, the sensitivity analysis found groundwater extraction, hydraulic conductivity, application efficiency, and effective porosity to be the most sensitive parameters.

GBSDM and SAHYSMOD were linked using the component modeling approach. Vensim Dynamic Link Libraries (DLL), python, and Visual Basic for Application (VBA) in MS Excel were used as linking tools. MS Excel was used as the wrapper to exchange information between the socio-economic and physical system components. Use of Excel as a wrapper increases model transparency and provides the opportunity for end users to manipulate data and evaluate policies. Both models exchange their output at a seasonal time step throughout the time period from 1980 to 2010. Six scenarios, including a base case scenario, one past implemented policy (i.e. Salinity Control and Reclamation Project (SCARP)), and various alternative management options for improving and reallocating canal water supply were tested. Spatial and temporal maps of changes in soil salinity, farm income, and water availability were prepared to evaluate the effects of the tested management options at the watershed scale. Policies were also evaluated for economic and environmental trade-offs through various performance indicators such as soil salinity, water availability, farm income and groundwater drawdown. The results clearly showed that canal lining and reallocating irrigation supplies had the potential to improve salt-affected areas. However, canal lining requires government support in the form of subsidies. The initial years of simulation suggest SCARP is the best management option although it might have positive impacts only if implemented intermittently. The continuous operation of SCARP may cause increased salt concentrations in the crop root zone due to secondary salinization. The SCARP policy results were in agreement with past SCARP monitoring studies.

The overall benefits of the proposed coupled model (P-GBSDM) are the provision of additional strengths to SAHYSMOD by incorporating socio-economic processes through stakeholder engagement. Furthermore, the developed integrated model is capable of performing analyses that SAHYSMOD was not able to simulate, such as changes in farm income, spatial predictions of water availability, and the evaluation of economic and environmental trade-offs.

RÉSUMÉ

Le nombre d’intervenants dans la modélisation de l'environnement a augmenté considérablement au cours des vingt dernières années. De nombreux programmes de planification et de gestion des ressources en eau font cependant face à d’importants défis lorsqu’ils essayent de développer des méthodes de gestion de l’environnement dans les pays en développement. Ces défis sont exacerbés par le manque de méthodes demandant peu d’investissements de temps, de finances, ou de compétences en modélisation. La présente étude vise à relever ces défis en développant un cadre de modélisation par étapes s’appuyant sur un modèle physique complémenté par un modèle socio-économique fourni par les parties prenantes, ceci pour la région Rechna Doab du Pakistan.

Des modèles des dynamiques des systèmes participatifs (MDSP) ont été développés sous des conditions de compétences, ressources financières et temps limités. Ils ont été développés en communiquant avec les acteurs potentiels (par exemple, les fermiers locaux, les experts et les représentants du gouvernement) et en représentant leurs points de vue et leurs idées pour des politiques potentielles sous la forme de diagrammes de boucles causales (DBC). Un modèle qualitatif de l'ensemble du système du bassin versant a été créé en combinant les diagrammes causals de chaque acteur. En prenant en compte de manière rigoureuse les contributions de chaque partie prenante dans le processus de modélisation, on peut ainsi s’assurer que les idées et les connaissances de ces acteurs locaux soient incluses, intégrant ainsi les composants physiques et socio-économiques dans l’étude d’un bassin versant. Cette approche améliore aussi les limites du modèle et son exhaustivité en veillant à ce que toutes les questions pertinentes et points de vue soient pris en compte.

Les processus physiques et socio-économiques clés ont été identifiés dans les DBC construits par les parties prenantes. Les composantes socio-économiques ont été modélisées par des sous-modules distribués dans un Modèle des Dynamiques des Systèmes Construit en Groupe (MDSCG). Chacun d’entre eux représente un secteur identifié par les intervenants, reproduisant les processus principaux suivants : pertes par infiltration, le stockage de surface, la quantité et la répartition de l’irrigation, l’extraction de l'eau souterraine, la pluviosité nette et le ruissellement, l’amélioration de l'efficacité de l'irrigation, la demande en eau agricole et, enfin, le revenu agricole. Des boucles de rétroaction entre les sous-modules distribués décrivent les interactions entre ceux-ci et permettent de simuler le comportement de l'ensemble du système à l'échelle du bassin versant.

Les tests standards furent utilisés pour valider la structure du modèle et son comportement dynamique, bâtissant ainsi la confiance vis-à-vis des résultats.

Les composantes physiques des DBC qualitatifs ont été modélisées avec SAHYSMOD (Modèle de salinité spatial agro-hydrologique). Le modèle distribué SAHYSMOD simule les changements des eaux souterraines, ainsi que le mouvement de l'eau et du sel dans la zone des racines des cultures à l'échelle du bassin versant. Le modèle a été calibré (1983-1988) et validé (1998-2003) sur des périodes de cinq ans en comparant le niveau des eaux souterraines observé avec le niveau simulé. Le modèle simule le niveau des eaux souterraines à un haut niveau de précision, avec un R^2 de 0,906 et de 0,925; une efficacité Nash–Sutcliffe de 0,812 et de 0,873 ; et une erreur moyenne de 0,436 et de 0,486 pour les périodes d'étalonnage et de validation, respectivement. Les analyses d'incertitude et de sensibilité du modèle obtenues par GLUE (Estimation d'incertitude par vraisemblance généralisée) indique que 70% des données observées se situe entre les limites d'incertitude de 95% et 5%. Ceci indique une bonne approximation des plages des paramètres sélectionnés pour l'étalonnage. L'analyse de sensibilité indique que les principaux paramètres de sensibilité sont l'extraction des eaux souterraines, la conductivité hydraulique, l'efficacité de l'application et la porosité nette.

Le modèle socio-économique a été couplé à SHAYSMOD en utilisant la modélisation par composants. MS Excel a été utilisé comme plateforme pour échanger les informations entre les composantes socio-économiques et physiques du système. L'utilisation d'Excel comme plateforme augmente la transparence du modèle et offre la possibilité pour les utilisateurs finaux de changer les paramètres et d'évaluer l'application de diverses politiques. Les deux modèles échangent leurs sorties à un intervalle saisonnier sur une période allant de 1980 à 2010. Six scénarios ont été testés, comprenant le scénario de référence, l'application d'une politique déjà appliquée dans le passé (Projet de contrôle et de réclamation de la salinité, SCARP), ainsi que de diverses options de gestion alternatives d'amélioration et de réallocation de l'approvisionnement en eau. Des cartes spatiales des changements dans la salinité des sols, le revenu agricole et la disponibilité de l'eau ont été préparées pour évaluer les effets des options de gestion testées à l'échelle du bassin versant. Les impacts des diverses politiques sur des indicateurs de performances tels que la salinité des sols, la disponibilité de l'eau, le revenu agricole et les prélèvements des eaux souterraines ont été analysés pour évaluer les compromis que ces politiques offrent entre les enjeux économiques et environnementaux.

Les résultats montrent clairement que le gainage des canaux et la réallocation de l'irrigation ont le potentiel d'améliorer les zones de haute salinité. Il est à noter que le gainage des canaux requiert une aide gouvernementale par le biais des subventions. Les résultats des premières années des simulations suggèrent que SCARP serait la meilleure option de gestion. Cependant, tandis que l’implémentation intermittente de SCARP peut mener à des impacts positifs, l’implémentation continue au long terme a le potentiel d’augmenter la salinité de la zone racinaire des cultures par biais de la salinisation secondaire. Les prédictions du modèle des résultats de l’implémentation de la politique SCARP concordent avec les études précédentes des impacts de cette politique.

Les bénéfices du modèle couplé (P-MDSCG) incluent l’incorporation des processus socioéconomiques par biais de l’implication des parties prenantes, ce qui n’est pas possible avec SAHYSMOD tout seul. En sus, le modèle intégré développé dans cette étude est capable de prédictions et d’analyses que SAHYSMOD ne peut simuler, incluant l’impact des changements en revenus agricoles, des prédictions spatiales de la disponibilité de l’eau et l’évaluation des compromis entre les enjeux environnementaux et économiques.

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I would like to dedicate this thesis to the loving memory of my mother, whose prayers make every difficult task possible for me.

FORMAT OF THE THESIS

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, which are as follows:

"As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript-based thesis must conform to the following:

1. Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly-duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis.)
2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.
3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following:

(a) A table of contents;

(b) An abstract in English and French;

(c) An introduction which clearly states the rational and objectives of the research;

(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper);

(e) A final conclusion and summary;

1. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g. in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

2. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this statement at the doctoral oral defense. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the “coauthored papers”.

CONTRIBUTIONS OF AUTHORS

The chapters of this thesis have been prepared for publication in peer reviewed journals and presented at scientific conferences. The author of this thesis was responsible for stakeholder engagement, system dynamics model development, calibration, validation, uncertainty and sensitivity analysis, and the preparation of manuscripts for publication. Dr. Shiv Prasher is the thesis supervisor and gave advice on model conceptualization, development, testing and evaluation. He was also involved in the editing and review of the manuscripts. Dr. Jan Adamowski is the thesis co-supervisor, and provided advice on system dynamics modeling, technical issues, model testing, and evaluation and was involved in review and editing of the manuscript.

Dr. Raffaele Albano, Research Associate at the School of Engineering, University of Basilicata, Italy, Mr. Johannes Halbe PhD candidate in the Bioresource Engineering Department at McGill and Mr. Julien Malard PhD candidate in the Bioresource Engineering Department at McGill contributed in terms of technical support for the research and also aided in the editing process.

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LIST OF ABBREVIATIONS

AET	Actual Evapotranspiration
CLDs	Causal Loop Diagrams
CN	Curve Number
DEM	Digital Elevation Model
DLR	Directorate of Land Reclamation
DSS	Decision Support System
ECe	Electrolyte Concentration of Extract
ESP	Exchangeable Sodium Percentage
ET	Evapotranspiration
EU	European Union
FOs	Farmer Organizations
GB-PSDM	Group Built Physical System Dynamics Model
GIS	Geographic Information Systems
GLUE	Generalized Likelihood Uncertainty Estimation.
GWP	Global Water Partnership
ID	Irrigation Department
IWASRI	International Water Logging and Salinity Research Institute
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
LEACHM	Leaching Estimation and Chemistry Model
NGOs	Non-Governmental Organization
NSE	Nash Sutcliffe Modeling Efficiency
Obs.	Observed
OFWM	On Farm Water Management
PET	Potential Evapotranspiration
PIDA	Provincial Irrigation and Drainage Act
PPSGDP	Punjab Private Sector Groundwater Development Program
PSDM	Participatory System Dynamics model

R^2	Coefficient of Determination
REC	Republic Engineering Corporation
RMSE	Root Mean Square Error
RS	Remote Sensing
SAHYSMOD	Spatial Agro Hydro Salinity Model
SAR	Sodium Adsorption Ratio
SCARP	Salinity Control and Reclamation Project
SCS	Soil Conservation Services
SDM	System Dynamics Model
SIC	Simulation of Irrigation Canal
Sim.	Simulated
SMO	Soil Monitoring Organization
SSRI	Soil Salinity Research Institute
SWAP	Soil-Water-Atmosphere-Plant
UNCED	United Nations Conference on Environment and Development
USSL	US Soil Salinity Laboratory
WAPDA	Water and Power Development Authority
WASID	Water and Soils Investigating Division
WTD	Water Table Depth

CHAPTER 1: **Introduction**

This research describes the development of an innovative integrated modeling framework which coupled a stakeholder-built socio-economic model with a physical model. This integrated model was applied to an assessment of soil salinity management policies in the Rechna Doab sub-basin, Pakistan. Stakeholders were engaged in model development which resulted in the incorporation of extensive local knowledge as well as preferred policy options and produced a comprehensive and detailed model. Running the model simulation under arid conditions characteristic of areas with problems of soil salinity increased the applicability of the model in other parts of the world, such as China, Australia and India.

The incorporation of socio-economic and physical components allowed for the evaluation of both physical and socio-economic uncertainties and their effects on each other. The benefits of this research included improved understanding of socio-environmental interaction feedbacks, stakeholder engagement in the modeling, and the evaluation of different sustainable management solutions to address soil salinity.

1.1 Soil Salinity as a Global Issue

Arid and semi-arid regions of the world face challenges of low crop yields and a limited availability of surface water resources. The low rainfall in these regions is typically erratic and poorly distributed and irrigation water must be transported from remote sources through large networks of irrigation canals and barrages, which cause both water logging and soil salinization. It is estimated that more than 30% of the world's irrigated land is affected by problems of salinity and the affected area increases by 2000 hectares per day on average (Qadir *et al.* 2014). Presently, 6 Mha of irrigated agricultural land in Pakistan, the focus of this research, is salt-affected, causing a 62% loss in agricultural income (Tanwir *et al.* 2003).

1.1.1 Soil Salinity Causes and Sustainable Management Challenges in Pakistan

In Pakistan, soil salinity is largely attributable to water logging due to a vast network of unlined canals and management activities have focused on controlling groundwater levels through canal lining, tree plantation, and drainage projects (Kazmi *et al.* 2012). The majority of these current measures and policies (e.g. horizontal and vertical drainage, water course lining, land leveling etc.) are based on the advice of local and foreign consultants (e.g. International Water

Management Institute (IWMI), International Waterlogging and Salinity Research Institute (IWASRI), Soil Salinity Research Institute (SSRI)), who base their suggestions on the results of physical modeling studies (Aslam and Van Dam, 1998; Khan, 2003; Nasir *et al.* 2003) and site investigations (Asif *et al.* 1996; Rehman *et al.* 1997; Tabet *et al.* 1997). There are also many local farm level management solutions, such as scraping surface salts and applying gypsum and sulfuric acid to cultivated lands. However, these are short-term solutions and the problem eventually reoccurs due to the shallow water table.

During the last two decades of the 20th century, the Government of Pakistan took active measures to deal with water logging and salinity by initiating many Salinity Control and Reclamation Projects (SCARP). Project implementation was based on consultant site investigations (REC, 1978) and physical modeling studies without consideration of socio-economic-environmental interactions. The projects initially produced promising results but problems of secondary salinization soon arose caused by poor management (Kazmi *et al.* 2012). Thus, farmers continued the practice of using marginal quality groundwater even in areas with saline groundwater. The SCARP tubewell projects were halted in 2000 due to poor performance, high costs and the short operational life of the associated infrastructure (Ghumman *et al.* 2012). Project discontinuation resulted in clogged drains due to weed growth and caused brackish water to accumulate on agricultural land. The high operational cost of SCARP tubewells compelled the government to implement public-private partnerships, such as the Punjab Private Sector Groundwater Development Program (PPSGDP), to transfer ownership of tubewells to the private sector (Horinkova, 2002). The lessons learned from the SCARP and PPSGDP projects highlighted the importance of stakeholder participation and demonstrated that sustainable management solutions can be developed through effective stakeholder engagement in project design and implementation.

The social and economic dimensions of soil salinity management policies have received little attention compared to the biophysical aspects. Some studies done in study area (Kijne, 2003; Tanwir *et al.* 2003) highlighted the importance of considering socio-environmental interactions through joint actions of government, non-governmental organizations (NGOs), and farmers, but unfortunately no social initiatives have been implemented due to small land holdings, the poor economic status of farmers, limited modeling and mathematical skills, and a lack of technical, political, and financial support. Participatory socio-economic modeling may help to enhance an understanding of the interactions between the social, economic and environmental aspects of the problem, as well as aid in identifying acceptable policy decisions at the community level.

1.1.2 Research Theme

The social, economic and environmental components of a system are considered as the three pillars of sustainability. Their importance in sustainable management highlights the fact that human and ecological processes are interdependent and that the success of any sustainable management policy strongly depends on a consideration of socio-economic conditions in the area. Conventional physical modeling techniques for soil salinity, such as LEACHM, DRAINMOD-S, SALTMOD, SWAP, SAHYSMOD and HYDRUS (Hutson and Wagenet, 1989; Kandil *et al.* 1995; Oosterbaan and de Lima, 1989; Van Dam *et al.* 1997) have significant limitations in terms of simulating sustainable solutions because of inaccuracies in predicting local conditions (e.g. demographic factors, supply and demand) and stakeholder perspectives (when and under what conditions they changed agricultural practices), as well as limited consideration of socio-economic factors (e.g. income, debt, subsidies and contributions). Conventional models define socio-economic conditions, such as income, benefits, subsidies, and GDP growth, exogenously, *i.e.* outside the system boundary, and use user-built socio-economic scenarios to test different policies (Davies and Simonovic, 2011). Therefore, they suggest policies without considering human, social, and environmental interactions. The exogenous consideration of socio-economic conditions narrows the model boundaries and may limit the ability of models to suggest sustainable solutions under specific conditions (Nutt, 2002).

The sustainable management of land resources and the development of better policy decision under conditions of limited resources requires a full understanding of soil salinization processes on a holistic scale using improved tools such as integrated models. The methodology proposed in this research addresses such limitations by combining the strengths of a well-tested agro-hydrological soil salinity physical model with a group-built system dynamics model. The system dynamics model is meant to represent stakeholder perceptions and socio-economic conditions of the study area. Integrated participatory model building connects various physical-socio-economic systems and explores the interactions between them through a series of internal feedback loops. Integrated participatory models can be effectively used to investigate the broader feedback effects of different soil salinity management policies, including those related to drainage, conjunctive water use, water allocation, and improvements in irrigation efficiency through canal lining or using advanced irrigation methods. It also provides the best means of to increase our understanding of the watershed in a larger context, highlighting the unforeseen consequences of human-environment interactions, analysing stakeholders' proposed policy options and designing alternative solutions.

The integrated modeling tool developed in this research consists of a stakeholder-built system dynamics model and a physical soil salinity model; Spatial Agro-Hydro-Salinity Model (SAHYSMOD). System dynamics models help simulate the non-linear behavior of complex systems through stocks and flows, internal feedbacks, and delays (Sterman, 2000). They provide a flexible modeling platform for 'big picture thinking' in order to see the broad systems view of sustainability. SAHYSMOD is a well-developed, spatially distributed, watershed-scale, physical soil salinity model that has been successfully applied in various arid regions of the world (Akram *et al.* 2009; Desta, 2009; Kaledhonkar and Keshari, 2007; Liaghat and Mashal, 2010; Singh and Panda, 2012a). The strengths of each model are combined by linking and applying them to describe the physical changes in soil salinity attributable to human interactions.

This research is innovative in three aspects:

1. To date, no attempt has been made to develop a simple and easily adoptable methodology of stakeholder initialization using a system thinking approach. The developed approach will help to address issues of cost, time and expertise which are usually considered significant hurdles to widespread adaptation of participatory modeling in many developing countries.
2. To date, no attempt has been made to develop a calibration, uncertainty and sensitivity analysis procedure of SAHYSMOD using the Generalized Likelihood Uncertainty Estimation (GLUE) technique. The developed procedure will be useful for distributed models, like SAHYSMOD, in a data limited environment. In addition, this methodology will aid in investigating uncertainties in model results which have never been explored before.
3. To date, no attempt has been made to dynamically link a physical model with a system dynamics model using a component modeling approach. The dynamic feedback between both modeling platforms helps in simulating human-environment interactions. The simulated results point to social-economic aspects of soil salinity that have not yet been considered by the other modeling studies.

1.2 Research Questions and Objectives

The main purpose of this research is to model human-environment interactions to improve soil salinity management through a distributed integrated participatory physical-socio-economic model. The developed model will help to address scientific and policy-based uncertainties through simulating stakeholder-proposed scenarios and evaluate them through environmental and economic trade-offs. For the integrated participatory modeling of the physical and social elements of the soil salinity system, the flow of research goes as follows:

- Potential stakeholders were identified and engaged through stakeholder-built Causal Loop Diagrams (CLDs). The individual group built CLDs were merged and then classified into thematic maps for evaluating the details of different aspects and simplifying the model structure for quantification purpose (see Chapter 3).
- Thematic maps on agricultural, social, environmental, and economic aspects of the system were quantified, linked through feedbacks and tested through system dynamic model structural and behavioral validation testing procedures (see Chapter 4).
- The physical components of the study area were parameterized through a calibrated and validated physical soil salinity model (SAHYSMOD). The uncertainty and sensitivity analysis of SAHYSMOD was carried out using the GLUE technique (see Chapter 5).
- The physical model (SAHYSMOD) (calibrated in Chapter 5) was linked with the Group-Built System Dynamics Model (GBSDM) (developed and tested in Chapter 4) to develop a coupled Physical and Group-Built System Dynamics Model (P-GBSDM) (see Chapter 6).
- Simulation experiments were conducted through P-GBSDM to analyze the proposed policy options of stakeholders through environmental and economic trade-offs (see Chapter 6).

This research addresses the following sustainability related questions:

1. How can participatory modeling be effectively applied in developing countries to meet the challenges of low expertise, financial resources, and time?
2. Can a highly-detailed model developed from simplified stakeholder-built qualitative models reveal important lessons about watershed management policies?
3. Which policies are helpful in producing beneficial results for sustainable land and water resource management and what are their economic and environmental impacts?

Loose coupling of the physical model (SAHYSMOD) with the flexible modeling environment of system dynamics, through easily accessible and commonly available integration tools (such as python, Excel and Vensim), helps model applicability for stakeholders, policy makers and implementers in the study area. Full integration of a physical-based model SAHYSMOD with a system dynamics model combines their strengths and results in a final model that is capable of evaluating several stakeholder-derived scenarios for soil salinity management with human-environment interactions. Furthermore, the integrated model is capable of performing analyses that SAHYSMOD was not able to simulate alone. These include changes in farm income, spatial prediction of water availability and an evaluation of economic and environmental trade-offs.

The main objective of this research is to develop a comprehensive and user-friendly integrated participatory modeling framework for soil salinity management at the watershed scale by coupling a physical model (SAHYSMOD) with a stakeholder-built system dynamics model.

The specific objectives of the research are to:

1. Develop a simple and detailed approach to identify and then involve stakeholders, and use qualitative CLDs to incorporate stakeholder views and policy options in participatory model building;
2. Develop a system dynamics model for the irrigated arid region of Rechna Doab, Pakistan, from the qualitative CLDs (Objective 1) through a stock and flow model, in order to simulate socio-economic conditions and various stakeholder-preferred management options;
3. Calibrate and validate SAHYSMOD along with its sensitivity and uncertainty analysis for simulation of salt and water balances in an irrigated arid region of Rechna Doab, Pakistan;
4. Develop an integrated distributed participatory model by linking SAHYSMOD (Objective 3) with a group built system dynamics model (Objective 2) to simulate alternative soil salinity management options through social-economic-environment interactions; and
5. Perform different simulation scenarios with the integrated distributed participatory model (Objective 4) to evaluate the environmental and economic trade-offs of stakeholder-proposed policies.

The study was conducted in the Haveli internal command area of Rechna Doab, Pakistan. The study area lies on the downstream side of the Haveli canal command and has an arid climate.

The majority of farmers are poor with an average land holding size of 3.85 hectares (Kiani, 2008). Being a downstream area canal, water supplies are insufficient and farmers are highly dependent on groundwater extraction; 75% of farmers use groundwater of marginal quality to irrigate their crops (Rehman *et al.* 1997). Groundwater depth varies from 3 to 6 metres, and groundwater electrolyte concentrations exceed 1500 ppm in the central portion of the basin (IWASRI, 2005). The traditional irrigation practice in the region, known as a warabundi system, operates on a turn-taking basis, where a farmer can take canal water only when it is their turn.

1.3 Thesis Outline

The thesis has been written as a series of manuscripts, each of which contributes to the above stated objectives.

Existing literature on soil salinity processes, physical soil salinity models, stakeholder engagement with participatory modeling approaches, system dynamic models, and integrated/coupled models is reviewed in Chapter 2.

The literature review is followed by four connected manuscripts. The first manuscript (Chapter 3) discusses a qualitative modeling technique through stakeholder engagement using CLDs.

The second manuscript (Chapter 4) discusses the detailed quantification of qualitative CLDs through four modules. A detailed discussion of the theoretical basis, mathematical equations and their associated parameter values, and linkages between the sub-models is presented.

The third manuscript (Chapter 5) discusses the calibration and validation of SAHYSMOD in the study area for model parameterization. Uncertainty and sensitivity analysis of SAHYSMOD is carried out using the Generalised Likelihood Uncertainty Estimation Technique (GLUE) (Beven and Binley, 1992)

The fourth manuscript (Chapter 6) discusses the model coupling approach used to link the physical model SAHYSMOD with the system dynamics model for the development of an integrated distributed stakeholder built model. Applications of the integrated participatory model are explored through a series of experiments to analyze the policy options proposed by stakeholders, and their economic and environmental impacts. This section highlights the significance of this work and explains how large-scale feedback-based modeling is helpful in illuminating the effects of policies in a broader context.

Chapter 7 discusses the conclusions derived from the most important results of this research, and Chapter 8 lists the major contributions to this field of study and recommendations for future research.

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CHAPTER 2: **Literature Review**

The prime focus of this research is to develop a user friendly, integrated, participatory modeling framework which is achieved by coupling a physical model with a group built system dynamics model. The complete framework of the research consists of four key components:

1. A physical model to simulate the salt and water balance within the crop root zone.
2. A qualitative participatory model for stakeholder engagement.
3. A quantitative socio-economic model of the study area, based on qualitative participatory models, using a system dynamics modeling approach
4. Linked physical and socio-economic models to create a comprehensive, integrated, participatory modeling framework.

Following this structure, the literature review is divided into four sections. The first section reviews the physical modeling of the process of soil salinization and includes subsections describing the soil salinity process, its causes and effects and the model selection criteria for the present research. The second section focuses on participatory modeling approaches and describes previously used techniques as well as the novel approach used in this research. The third section reviews system dynamics modeling in the context of simulating the dynamics of socio-economic processes and includes subsections on system dynamics modeling components and past applications of dynamics models in soil salinity process simulations. The final section covers model-coupling approaches and provides details on the integrated model that was developed.

2.1 Soil Salinity

Salinization is generally defined as the excessive increase of water-soluble salts in the crop root zone. The process of soil salinization is highly dependent on the quality of irrigation water, irrigation management such as conjunctive water use, and the drainage potential of the soil. High salt concentrations adversely affect plant growth and the livelihood strategies of small farmers.

2.1.1 Parameters for Soil Salinity Measurement (pH, EC)

According to the US Soil Salinity Laboratory (USSL) (Richards, 1954), salt-affected soil can be classified into three categories. The classification is based on the electrolyte concentration of the saturation extract (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) and pH (Table 2.1).

Table 2.1. Salt affected soil classification criteria (Richards, 1954)

Criterion	Normal	Saline	Sodic	Saline-sodic
EC_e (dS m^{-1})	< 4	> 4	< 4	> 4
SAR	< 13	< 13	> 13	> 13
ESP	< 15	< 15	> 15	> 15
pH	< 8.5	< 8.5	> 8.5	< 8.5
Condition	Flocculated	Flocculated	Dispersed	Flocculated

High concentrations of salt in the crop root zone result in low osmotic potential and reduced crop water uptake. A high pH not only affects soil microbiological activities but also reduces plant growth due to low nutrient uptake. Of the three categories of salt-affected soils, sodic soils are the most difficult to manage due to their propensity for swelling or dispersion, extremely low hydraulic conductivity and poor aggregate stability.

2.1.2 Physical Modeling of Soil Salinity

Build up of salt in the crop root zone due to the use of marginal quality irrigation water, also known as secondary soil salinization, is a complex process whose modelling requires a full understanding of the interactions between human interventions and the salinization process. According to Farifteh *et al.* (2008) salinization is a generally irreversible series of processes which occur within a decade and result from the interaction of several factors such as irrigation, tillage, and cropping pattern etc. While no climatic zone in the world is free from the risk of soil salinization (Farifteh *et al.* 2008; Madyaka and Farshad, 2008), the phenomenon is most commonly observed in arid and semiarid regions (Desta, 2009). In more humid regions rainfall helps dilute excess salts, rendering soil salinity an issue of minor concern.

Various techniques have been employed to monitor and eventually control salinity problems: (i) use of artificial neural networks for prediction (Patel *et al.* 2002) (ii) geographic information systems (GIS) and remote sensing for spatial modelling and temporal prediction (Abbas *et al.* 2010; Abdelfattah *et al.* 2009; Dehni and Lounis, 2012; Desta, 2009), (iii) use of geo-statistical techniques for the estimation of the spatial extent of salinization (Navarro-Pedreño *et al.* 2007), (iv) spectral reflectance monitoring (Farifteh *et al.* 2010) and (v) use of an EM38 earth conductivity meter for the measurement of soil salinity (Yao and Yang, 2010). These techniques produce reasonable estimates of soil salinity in the field but fail to predict its future impact in "what-if" situations.

Numerical models are accepted as helpful tools to understand interactions and gain insight into the processes occurring within complex systems. They also provide a better platform for assessing "what-if" situations with the goal of improving resource management and optimizing the sustainability of proposed policies. Many studies have used numerical modeling tools to understand the distribution and dynamics of soil salinization (for example, Bahceci and Nacar, 2007; Kale, 2011; Lin and Garcia, 2008).

Models dealing with the hydro-salinity of agricultural lands generally consist of two components: (i) a hydrological module which controls irrigation, evapotranspiration and groundwater flow for simulating the behavior of the water table and soil moisture movement in the unsaturated zone, and (ii) a solute movement module which controls the processes of advection, dispersion and adsorption. Solute transport models have been classified according to different criteria, such as seasonal and transient models (Madyaka and Farshad, 2008), mechanistic, stochastic and empirical models (Bastiaanssen *et al.* 2007) and steady-state and transient models for leaching estimation (Corwin *et al.* 2007). Water flow and solute transport in soils are generally addressed in one of two ways (Askri *et al.* 2010):

i. A mechanistic approach based on Richard's equation for the movement of water, coupled with a differential salinity dispersion equation for the simulation of salt movement, *e.g.* SWAP (Van Dam *et al.* 1997), HYDRUS (Šimůnek *et al.* 1998), LEACHM (Hutson and Wagenet, 1989), and UNSATCHEM (Šimůnek *et al.* 1996). In these models, land regionalization is carried out based on land use as well as soil and topography. However, given their over-parameterization and large data requirements, these models are often impractical.
ii. A characterization of a cell's average response rather than specifying the exact physical processes and their variation within the cell — as found in several water balance-based seasonal models, *i.e.* SALTMOD (Oosterbaan and de Lima, 1989), SAHYSMOD (Oosterbaan, 1995), SWAGMAN (Robbins *et al.* 1995), and CATSALT (Tuteja *et al.* 2002). These models treat agricultural lands in a lumped manner by assuming a uniform distribution of cropping, irrigation, and drainage characteristics over the entire area. Some of the most widely used solute transport models and a few case studies are presented in Table 2.2.

Table 2.2. Widely used solute transport models and their case studies

Model	Study Objective	Country of application	Source
CATSALT Tuteja *et al.* (2002)	Assessment of salt and water balance for Boorowa River catchment affected by dryland salinity	Australia	Vaze *et al.* (2004)
	Use of a partial mutual information technique for assessment of salt and water balance in ungauged catchments		Coff *et al.* (2009)
DRAINMOD-S Kandil *et al.* (1995)	Simulation of drainage design criteria for water and salinity management for central Kızılırmak Basin	Turkey	Kale, (2011)
HYDRUS Šimůnek *et al.* (1998)	Optimization of soil hydraulic parameters and downward bottom flux under different soil salinity levels	USA (California)	Singh and Wallender, (2010)
	Evaluation of salt accumulation under subsurface drip irrigation	USA (Arizona)	Roberts *et al.* (2009)
	Modeling of water movement and solute transport	Portugal, Senegal	Ndiaye, Molénat *et al.* (2008); Ramos, Šimůnek *et al.* (2011)
	Modeling for improved		Forkutsa, Sommer *et al.* (2009)

	management strategies to update irrigation standards	Uzbekistan	Corwin, Rhoades *et al.* (2007)
	Estimation of leaching requirements	USA	
LEACHM Hutson and Wagenet, (1989)	Simulation of solute leaching with low quality irrigation water	Iran	Kolahchi and Jalali, (2006)
SAHYSMOD Oosterbaan, (2005)	Study of factors affecting the design and operation of a bio-drainage system	Iran	Akram, Kashkouli *et al.* (2008)
	Spatial and temporal prediction of salinization	Thailand	Desta, (2009)
SALTIRSOILs Visconti *et al.* (2006)	Study of the effects of irrigation water quality and management scenarios on root zone salinization	Spain	Visconti, de Paz *et al.* (2012)
SALTMOD Oosterbaan and de Lima, (1989)	Analysis of salt and water balance	India	Singh, Bhattacharya *et al.* (2002); Srinivasulu, Sujani Rao *et al.* (2004)
	Scenario analysis of salinity management by changing irrigation depth, water quality and drain spacing	Turkey	Bahçeci and Nacar, (2007)
SWAGMAN Robbins *et al.* (1995)	Optimization of land use for water table	Australia	Khan, O'Connel *et al.* (2008)

	and soil salinity management.		
SWIM Verburg, (1996)	Modeling the spatial distribution of potassium concentration in soil profile under varying irrigation conditions	India	Purandara, Varadarajan *et al.* (2008)
UNSATCHEM Šimůnek *et al.* (1996)	Evaluation of the use of saline water and water application rate on root zone salinization	Iran	Rasouli, Kiani Pouya *et al.* (2012)

Physical model in Table 2.2 focuses on unsaturated zone of soil profile only. Moreover, all of them except SWAGMAN (Robbins et al. 1995) are field scale models missing groundwater component. SWAGMAN on the other hand is not a freely available open source model. Selection of the physical model for this research was based on model capabilities such as free source code and watershed scale simulation of groundwater contribution in secondary salinization. Such capabilities helped in simulating the physical processes described in the stakeholders' mental models or causal loop diagrams, such as vertical drainage, crop rotation and conjunctive water use. The model was based on a simple seasonal water balance approach, which simulates average cell responses rather than specifying physical variations within them. Our study area was divided into a grid of 279 rectangular polygons (215 internal and 64 external). These divisions are smaller than the grids used in previous SAHYSMOD studies (Desta, 2009; Singh *et al.* 2012a) in order to give a more accurate representation of catchment attributes such as spatial variation in the soil series and cropping patterns. The model exported the data from all polygons to MS Excel.

2.1.3 Past Salinity Modeling Research in Pakistan

Due to its prevailing arid to semi-arid conditions, Pakistan's Indus Basin is under continuous threat of soil salinization. Soil salinity first received attention in 1895 when it was linked to problems of waterlogging arising from irrigation canal seepage. Management focused on controlling the groundwater table through canal lining (from 1895 onward), tree plantation, surface and interceptor drains (from 1930 onward), and vertical drainage by way of tubewells (from 1940 onward) (Kuper, 1997). The 1970 Soil Survey of Pakistan found the causes of soil salinity to be much more diverse than originally thought and identified rock weathering, rise of the groundwater table and use of poor quality irrigation water primarily responsible for the increase in soil salinity in the Indus Basin region.

In 1943, the Directorate for Land Reclamation (DLR) conducted the first visual salinity survey of the Indus Basin. Based on survey results they advised the Irrigation Department (ID) to provide extra water to salinity-affected areas during the flood season in order to reclaim salinized lands. However, the already tremendous pressure on canal water usage left hardly any water for reclamation and the Irrigation Department did not sanction the extra water.

Different agencies — particularly the Water and Power Development Authority (WAPDA) and the Water and Soils Investigating Division (WASID) — employed a range of different techniques to conduct salinity surveys which covered the entire basin of the Indus plains. The International Irrigation Management Institute (IMII) and its partners also did some studies, but these surveys were within the scope of specific projects. Table 2.3 shows the inventory of different salinity surveys conducted in the Rechna Doab area in Pakistan. Kuper (1997) made an interesting comparison in the Chishtian sub-division of the Indus plains by digitizing the results of the 1960 and 1978 surveys and found a gradual decrease in soil salinity problems in those areas where canal water supplies were available to farmers.

Table 2.3. Inventory of soil salinity surveys conducted in Rechna Doab

Organization	**Year**	**Methods**
WASID	1960	Visual observation, aerial photographs
WAPDA Master Planning	1978	Sampling, visual observation
Cemagref/IIMI	1995	Remote sensing (Tabet *et al.* 1997)
DLR/IIMI	1996	Visual observation (Asif *et al.* 1996)
IIMI	1997	EM38 (Aslam *et al.* 1997)
IWASRI	2002	Visual observation

Nearly all soil salinity surveys classified the severity of soil salinity into four groups: non-saline (EC_e < 4 dS m^{-1}), slightly saline (EC_e 4-8 dS m^{-1}), moderately saline (EC_e 8-16 dS m^{-1}), and strongly saline (EC_e >16 dS m^{-1}) (Kuper, 1997; Qureshi, *et al.* 2002).

In Pakistan, soil salinity research leapt forward after the failure of the SCARPs, when the Dutch government initiated a project entitled "Managing irrigation for environmentally sustainable agriculture in Pakistan", under which a number of studies were conducted to understand the processes involved in soil salinity and sodicity (Aslam and Van Dam, 1998; Biggar, 1996; Condom *et al.* 1999). These studies all indicated that the continual use of poor quality tubewell water could cause irreversible sodification problems in irrigated soils. Such studies opened new avenues of research and led to the use of modeling techniques to evaluate the effects of water conservation programs, equitable distribution of water, and skimmed groundwater use on soil salinity (Kuper, 1997; Bastiaanssen *et al.* 2001; Qureshi, *et al.* 2004). Other modeling studies have predicted future groundwater trends in the face of changes in groundwater quality and quantity and have evaluated the performance of SCARP tubewells (Khan, 2003; Khan, *et al.* 2008). Table 2.4 summarizes the modeling studies implemented in the Rechna Doab area of Pakistan, along with their years and study objectives.

Table 2.4. Soil salinity models used in Pakistan

Model	**Study Objective**	**Source**
LEACHM Wagenet and Hutson, (1987)	To develop predictive capabilities for soil moisture flow and solute transport	Aslam and Van Dam, (1998)
MODFLOW 2000 Harbaugh *et al.* (2000)	Modeling of future groundwater trends due to changes in water table depth and quality	Qureshi, *et al.* (2004); Khan, *et al.* (2008)
SALTMOD Oosterbaan and de Lima, (1989)	Evaluation of the SCARP projects	Khan (2003)
SWAP Van Dam *et al.* (1997)	Irrigation management strategies for improved salinity and sodicity control Evaluation of design and operation of skimming wells for long-term sustainability of irrigated areas	Kuper (1997); Sarwar, *et al.* (2001); Qureshi, *et al.* (2004).
UNSATCHEM Šimůnek *et al.* (1996)	Study of soil salinization in relation to irrigation water quality and soil texture	Condom *et al*. (1999)

Most studies highlight the need for an integrated approach to salinity management research in order to identify appropriate government interventions by testing different policies (Kuper, 1997; Khan *et al*. 2009; Van Delden, 2009). However, due to the challenges such as complexity, funding, time and modeling skills required by the previous integrated modeling frameworks, only few studies incorporated socio-economic aspects into the dynamic processes involved in salinization. Kuper (1997), coupled an irrigation canal simulation model (SIC) and SWAP to create an integrated model. He studied reallocation of canal water and analysed the effect of equitable water distribution on soil salinity. He concluded that the area threatened by salinity could be reduced by 40% by reallocating canal water without affecting agricultural production.

Recognizing the importance of stakeholder participation, the Government of Pakistan initiated some institutional reforms such as the Punjab Irrigation and Drainage Authority (PIDA) in 2006 and the On-Farm Water Management (OFWM) project in 2001. However, due to conflicts between stakeholders and strong political opposition, progress on these projects has been slow (Bhutta and Smedema, 2007). This situation urgently requires a tool capable of integrating physical processes with socio-economic issues and resolving conflicts among stakeholders through a social learning process. The methodology proposed in this research will be helpful in addressing these challenges.

2.1.4 Model Selection

SAHYSMOD was selected from the available soil salinity physical models for several reasons:

1. It provides a wide range of flexibility in terms of agricultural practices such as farmer response to soil salinity, the option of horizontal, vertical, or surface drainage, conjunctive water use, and crop rotation due to changes in the soil salinity profile.
2. It addresses the majority of physical processes associated with soil salinity in the study area, which were identified by stakeholders in the first phase of the modeling study (see Inam *et al*. 2015).
3. It can evaluate policies of canal lining and tubewell abstraction for aquifer sustainability.
4. It is a spatially distributed model, thus helpful for recommending site-specific solutions while taking into consideration other factors such as low water availability due to the location of the farm on the canal network.

SAHYSMOD uses seasonal time step and seasonal input data to give seasonal outputs. Reasons of not using smaller input/output periods are as follows;

- Short-term (e.g. daily) inputs would require much information, which, in large areas, may not be readily available.
- This model is especially developed to predict long term trends, which are made on a seasonal (long term) rather than on a daily (short term) basis.

The number of seasons per year can vary from one (twelve-month duration) to four (three-month duration each). Seasonal salt and water balances are used as inputs. These are related to surface water hydrology (*e.g.* rainfall, potential evapotranspiration, irrigation and run-off) and groundwater hydrology (*e.g.* groundwater pumping, capillary rise and drainage). The technical details of SAHYSMOD are described in Chapter 5.

2.2 Participatory Engagement

Physical models are usually considered the best modeling tools to examine various "what-if" conditions for different scenarios and policy evaluations. However, most physical modeling-based policy recommendations have failed because the models were formulated without the involvement of key stakeholders. Nutt (2002), after a careful analysis of 400 strategic decisions in various contexts, found that half of the decisions 'failed' because decision-makers did not include the knowledge and interests of key stakeholders. Therefore, participatory modeling is incorporated as a key component of this research as a means of integrating local knowledge and socio-economic conditions with the physical system in order to develop an integrated modeling framework.

Over the past few decades, stakeholder participation in dealing with complex environmental problems has gained considerable importance in developing and developed countries. Table 2.5 summarizes the different periods of stakeholder participation history.

Table 2.5. Phases of stakeholder participation history

Year	Phase	Reference
1960s	Social awareness campaign	Van Tatenhove and Leroy, (2003)

1970s	Incorporating local perspectives in data collection and planning	Pretty, (1995a,b)
1980s	Participatory rural appraisal	Chambers, (2002)
1990s	Stakeholder participation as a norm in sustainable development	UNCED, (1992)
2000s	Growing "post-participation" consensus over best practices, learning from the mistakes and successes of this long history	Hickey and Mohan, (2004)

Stakeholder involvement has recently become an integral part of water resource planning in order to secure a precious resource, detect the system's critical issues, identify knowledge gaps, increase stakeholder understanding of a complex ecological and socio-economic system, resolve conflicts of interest, and facilitate decisions regarding long term policy analysis. Reed *et al*. (2009) and Reed (2008) provide a comprehensive review of different stakeholder engagement techniques. Many developing countries are altering their water resource plans and programs to ensure the inclusion and involvement of stakeholders (Baril *et al*. 2006; Jønch-Clausen, 2004; Petit and Baron, 2009). Examples of stakeholder engagement approaches (used mainly in developed countries) in the participatory modeling process include group model building (Langsdale *et al*. 2009), mediated modeling (Van den Belt, 2004), Bayesian networks (Chan *et al*. 2010), fuzzy cognitive mapping (Sperry and Jetter, 2012; van Vliet *et al*. 2010), companion modeling (Gurung *et al*. 2010) and shared vision planning (Werick and Palmer, 2004). However, these approaches normally require significant funding, time, and modeling skills. Another limitation is the need for large group meetings for stakeholder engagement. The main problem with group meetings is the poor attendance of stakeholders. For example, not all of the participants might be interested in attending meetings. Burgin *et al*. (2013), conducted a study of stakeholder engagement in water policy in Australia and reported that more than half the participants attended only one of 12 meetings. In another study, Videira *et al*. (2009) highlighted the issue of unstable group composition in a participatory river basin management modeling study carried out in Portugal. In addition, it is often difficult to capture an individual stakeholder's point of view or 'mental model' for a particular issue because, for example, some stakeholders might be reluctant to voice their opinions in the presence of government officials or their superiors in the organization. The unique participatory modeling approach developed in this study overcomes such limitations by formulating a cost and time effective approach that requires fewer mediation skills by omitting large group meetings. The proposed approach uses a system thinking tool: causal loop diagrams (CLDs). Facilitators travel to the stakeholders to guide the development of the individual CLDs. The details and procedure of the proposed approach are discussed in Chapter 3. The following section describes the components and details of the system dynamics modeling tool used to prepare CLDs and model the socio-economic component of the integrated model.

2.3 System Dynamics Modeling Components and Applications

System dynamics modeling was first developed and used by Forrester in the 1950's to understand the dynamics of industrial and urban systems (Forrester, 1958). Since then, system dynamics has been widely applied in various disciplines and has proven to be an excellent modeling tool for complex concepts. Based on an object-oriented approach, it can easily address increased complexity and significant changes in a scenario. System dynamics is based on the notion that the behavior of real world systems results from system structures formed through the feedbacks or interactions of different processes interacting within the system. According to Beall and Ford (2010) "when faced with complex, multi-stakeholder environmental issues, system dynamics has the greatest potential when used in a participatory fashion by scientists and managers working together with others who also have a stake in land management decisions". Such characteristics, as well as unique modeling features such as the incorporation of delays, feedbacks, flexibility and transparency (Sterman, 2000), make system dynamics a good candidate for the current modeling study. A widely-accepted system dynamics modeling simulation package, Vensim DSS, was employed in this study.

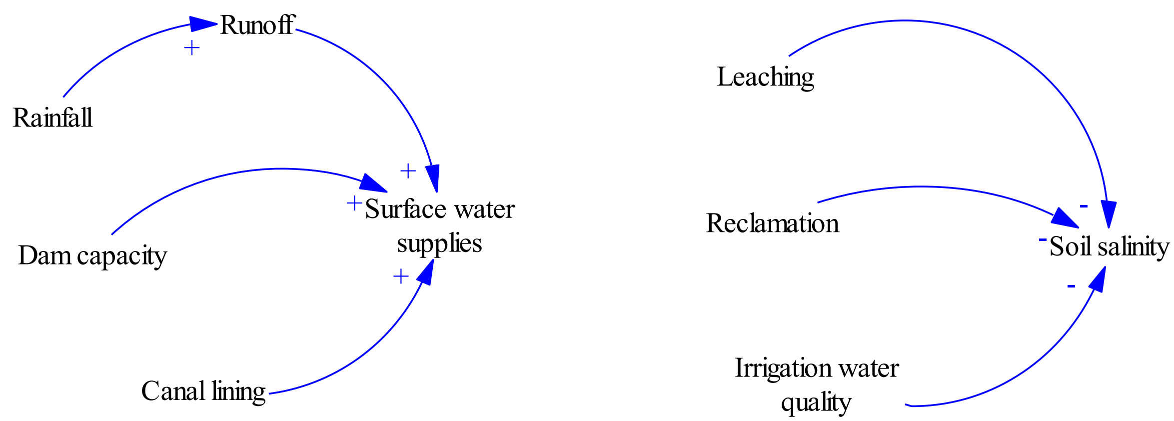
The following section gives an overview of the key system dynamics modeling concepts and components involved in the study. An application highlighting the importance of system dynamics in the field of water resources and soil salinity is discussed in Chapter 3.

Causal loop diagram:

Consisting of variables and causal links with positive or negative polarities, CLDs represent the mental models of the stakeholders. Linking different variables with causal links forms feedback loops which show the ultimate effect of an action on a problem variable.

Causal links:

Causal links join independent variables to dependent variables and they can have negative or positive polarities. The latter indicates a direct effect of the independent variable on the dependant variable, *i.e.* if the cause increases then the effect increases, or if the cause decreases then the effect will decrease. Meanwhile a negative polarity indicates an inverse effect of the independent variable on the dependant variable, *i.e.* if the cause increases then the effect will decrease, or if the cause decreases then the effect will increase.



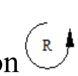
(a) (b)

Figure 2.1. Causal links with a) positive and b) negative polarities

Figure 2.1a shows the effect of runoff, dam capacity and canal lining (independent variables) on surface water supplies (dependent variable). All variables are connected with positive polarity arrows since an increase in any one of the independent variables will result in an increase in the dependent variable. Figure 2.1b illustrates negative polarity, or an inverse relationship between the dependent and independent variables; *i.e.* any increase in leaching, reclamation or irrigation water quality will reduce the extent of the soil salinity problem.

Type of Feedback Loop:

Feedback loops represent the system's qualitative behavior. There are two types of loops involved in system dynamics modeling.

Reinforcing loops are represented by the notation  and represent an exponential increase or decrease in a process. Figure 2.2 shows a reinforcing loop where government subsidies reduce farmers' tubewell pumping costs, which increases groundwater pumping, which, in turn, increases the water table depth from soil surface and therefore reduces groundwater quality by removing the top groundwater layer. This ultimately increases soil salinity due to the application of poor quality groundwater for irrigation. The increase in soil salinity will pressure the government to give more subsidies to farmers, which will then further exacerbate the soil salinity problem. Thus, according to this loop, soil salinity problems in saline groundwater areas will continue to increase in an exponential manner.

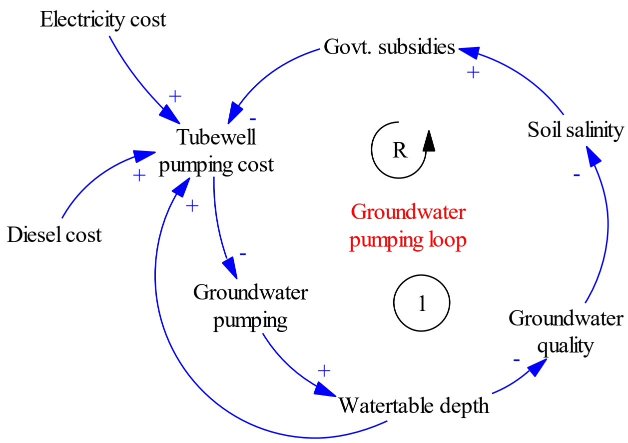


Figure 2.2. Groundwater pumping reinforcing loop

Balancing loops are represented by the notation B and try to balance or equilibrate the state of the system and bring it to a state of equilibrium, *i.e.* an increase in the value of the problem variable will generate a change across the feedback loop which will ultimately return to the problem variable and reduce its magnitude. Figure 2.3 shows a balancing loop, which ultimately balances or reduces soil salinity due to on-farm farm machinery use. Soil salinity will increase government subsidies, but in this case farmers will get soft loans for the purchase of a tractor or other farm equipment. This can be used to level their lands, which can improve irrigation efficiency, allow for salt leaching and ultimately reduce soil salinity.

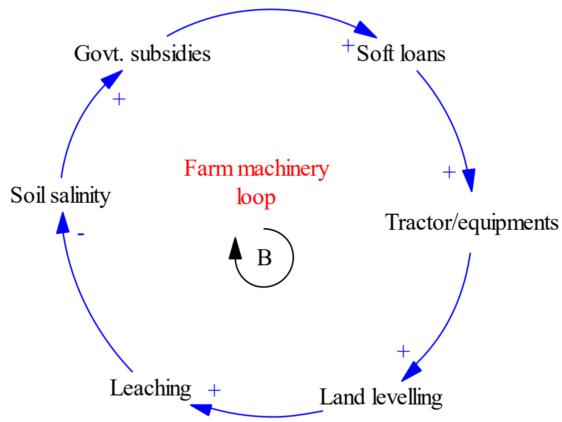


Figure 2.3. Farm machinery balancing loop

Stocks and Flows Diagrams:

Stocks and flows diagrams represent the quantified portion of the model where the relationships between different variables are defined in the form of mathematical relationships that, upon simulation, give numerical results. Notation used in stocks and flows diagrams are shown in Figure 2.4.

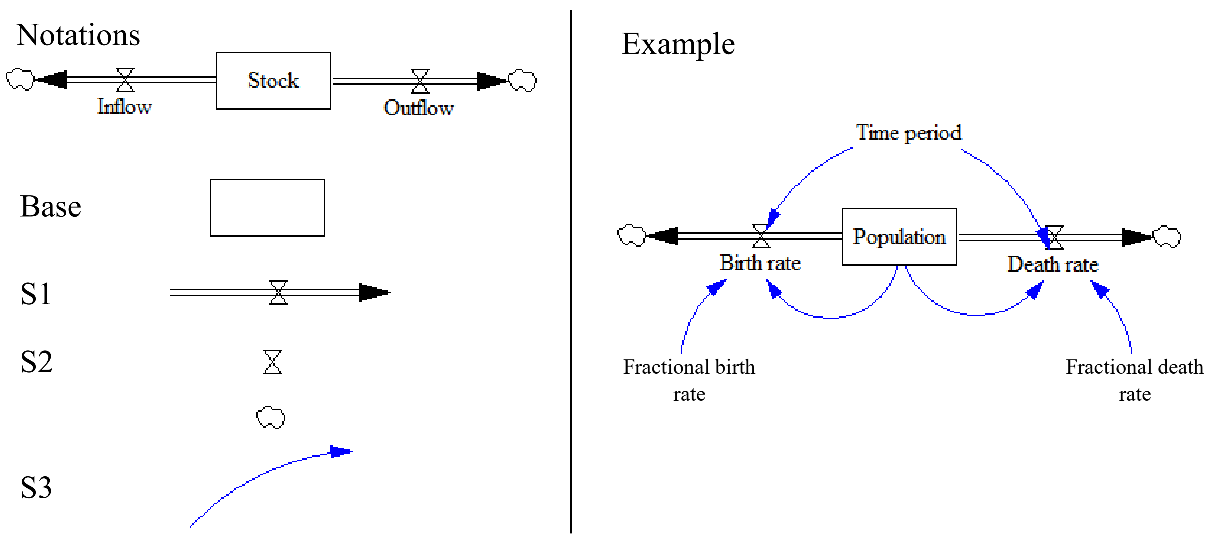


Figure 2.4. Notation used in stocks and flows diagrams with examples

- <u>Stocks (Levels):</u> Indicates any cumulative variable such as a reservoir or the area subject to soil salinity.

- <u>Flows (Rates):</u> Indicates variables that fill or drain the stock variable. Rate of soil salinity (area year^{-1}) can be considered an inflow to the saline area stock, while the rate of reclamation (area year^{-1}) can be considered as an outflow from the same stock.
- <u>Connectors (Arrows):</u> Represented graphically as arrows, connectors and their directions define the dependency relationship between variables.
- <u>Converter:</u> Disaggregate complex functions, they accept inputs in the form of algebraic relationships, graphs, or tables and transform an input into an output.

System dynamics modeling has been tested successfully and proven to be the most appropriate tool for expressing nonlinear relationships between the complex physical, socio-economic, and environmental systems (Dyson and Chang, 2005; Herrero *et al*. 2014; Prodanovic and Simonovic, 2007). After 60years of development, system dynamics has become a well-established modeling methodology and has gained importance in many practical and scientific fields, including but not limited to management, ecology, economics, education, engineering, public health, and sociology (Sterman, 2000). System dynamics modeling have been successfully used for water resources planning, policy analysis, sustainable development, and natural resource management (Ahmad and Simonovic, 2000; Bagheri et al. 2010; Dai *et al.* 2012; Davies and Simonovic, 2011; Hare *et al.* 2003; Prodanovic and Simonovic, 2007; Sendzimir *et al.* 2007; Stave, 2003). The application of system dynamics models to the field of soil salinity management, as per this research, is described below.

System dynamics modeling studies of soil salinity are uncommon: only three such studies have been published thus far (Giordano *et al*. 2010; Khan and McLucas, 2006; Saysel and Barlas, 2001). Two studies (Khan and McLucas, 2006; Saysel and Barlas, 2001) involve the development of a dynamic model based on physical processes only, while in the third study (Giordano *et al.* 2010) the soil salinity monitoring system was designed based on local knowledge and available resources. To the best of the author's knowledge, no salinity management study has explored the topic of using socio-economics in a system dynamics modeling. In this section, past research and the main flaws of associated models will be discussed.

Saysel and Barlas (2001), integrated four physical processes (irrigation, drainage, groundwater discharge and groundwater intrusion) to develop a dynamic simulation model of salt accumulation on irrigated lands. They tested different scenarios by evaluating system behavior under abandoned irrigation, irrigation water of different salinity levels, and reuse of drainage water. The research mainly focused on evaluating the simulated behavior of trends in soil salinity without the use of any real dataset to validate the model.

Khan and McLucas (2006), used a real data set from Australia's Murray-Darling Basin to develop reference modes to be used in system dynamics modeling of dryland salinity. Their research was based on the hypothesis that the removal of trees to make way for cultivation increased the rate of soil salinization. They classified the land into three categories: salt-affected land, land at risk of becoming salt-affected and land under natural vegetation. The whole model was developed without the active participation of stakeholders and lacked basic physical processes. Only a time delay in land clearing was evaluated for its resulting delay in salinity development.

Giordano *et al.* (2010) developed a soil salinity monitoring system with the use of system dynamics modeling. Although they highlighted the importance of stakeholder involvement in the modeling and monitoring process, they failed to apply these recommendations in a socio-cultural and institutional context. They used physical processes only for soil monitoring purposes.

The current study is innovative in the field of system dynamics modeling as well as physical modeling because it links a group-built system dynamics model representing local knowledge and socio-economic context with a well-tested watershed scale soil salinity model (SAHYSMOD). This strengthens both modeling systems by dynamically exchanging data between the two and simulating the effects of socio-economic changes on the physical system to enable better prediction of human-environment interactions. The following sections examine different approaches to model coupling used for the development of integrated modeling systems.

2.4 Model Coupling

Advancements in computational capabilities as well as the development of new modeling tools such as geographic information systems (GIS), remote sensing (RS), and Bayesian inference, among others, give new dimensions to conventional modeling by integrating hydrological, economic, social, and environmental components into integrated watershed management. These interdisciplinary approaches help in the development of more comprehensive modeling tools to address a wide spectrum of problems ranging from strategic-level decisions to design alternatives. The following sections provide details on integrated modeling approaches and their limitations. Based on the focus of the current research, this section has been divided into two parts, the first covers the development of integrated models for soil salinity management, while the second gives details on integrated modeling studies in the field of system dynamics modeling.

2.4.1 Integrated Modeling Studies of Soil Salinity

Laudien *et al.* (2008) developed an integrated modeling tool to evaluate the impact of water exploitation on groundwater and soil salinity changes and successfully used it in West Africa for the efficient management of scarce water resources with due consideration to salt build-up processes. The comprehensive model linked four existing micro-scale models of groundwater, irrigation water demand, domestic water demand and soil salinity using the ArcGIS engine. Model modules were loosely coupled through a component modeling or wrapper programming approach. Building models in a modular manner allowed users to maintain their implemented module or model equations. However, this integrated system was developed without any feedback between system components and therefore failed to simulate dynamic system behavior. Some studies attempted to address this limitation by translating process-based models into the dynamic modeling environment. For example, Nozari and Liaghat (2014) developed a system dynamics model with the main goal of estimating drainage water quality and quantity and the subsequent effect of drainage effluent on soil salinity. Their model was based on sub-models of water balance, salt balance and the convention-dispersion equation. They used a solid set approach, in which various model components were linked together to represent one unit. However, none of the above studies attempted to include stakeholder perceptions and socio-economic issues in the soil salinity modeling process. The coupling of expert models (physical models) and system dynamics models (group-built socio-economic models) demands a transparent and flexible coupling approach that can be applied in participatory processes.

A number of past modeling studies tried to link physical and social system components through feedbacks between processes (Fernández and Selma, 2004; Li and Simonovic, 2002; Smith *et al.* 2005; Stave, 2003) to closely mimic their real-world equivalents. However, integrated models are not widely accepted by stakeholders due to the limited participation of end users in their development and their use of complex modeling tools unfamiliar to stakeholders (Prodanovic and Simonovic, 2010).

2.4.2 Integrated Modeling Studies of System Dynamics Modeling.

To the best of the author's knowledge, there is only one integrated modeling study of system dynamics modeling. Prodanovic and Simonovic (2010), coupled a system dynamics modeling program with the HEC-HMS hydrological model. The integrated model was developed by translating both models into a common Java language and coupling them in a system dynamics modeling environment. They used the coupled models to study the effects of socio-economic factors and climate change on the Upper Thames watershed in Ontario, Canada. They obtained significant results when modeling the interaction between human behavior and physical processes, indicating the usefulness of such an approach.

Model coupling by translating the source code into Java, however, requires a great deal of effort and also restricts the applicability of the resulting model. Moreover, further modification requires a programming professional, and the model therefore cannot be immediately applied to other projects with different stakeholders. Such a system is not user-friendly and cannot be used by the stakeholders themselves to evaluate different policies. This doctoral research will use commonly applied modeling tools to develop a flexible user-friendly system that can be easily adopted by all stakeholders.

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CONNECTING TEXT TO CHAPTER 3

This chapter describes the development of a unique and effective stepwise approach to identifying and engaging stakeholders in developing countries in the participatory modeling process under the constraints of limited time, expertise, and financial resources. The approach developed aids in selecting key potential stakeholder among diversified groups of stakeholders and explicitly incorporates their views and policy options in the form of causal loop diagrams. The qualitative models thus developed provide a holistic view of the whole system with socio-economic and physical process interactions.

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CHAPTER 3: **Using Causal Loop Diagrams for the Initialization of Stakeholder Engagement in Soil Salinity Management in Agricultural Watersheds in Developing Countries: A Case Study in the Rechna Doab Watershed, Pakistan**

Azhar Inam, Jan Adamowski, Johannes Halbe, Shiv Prasher

Abstract

Over the course of the last twenty years, participatory modeling has increasingly been advocated as an integral component of integrated, adaptive, and collaborative water resources management. However, issues of high cost, time, and expertise are significant hurdles to the widespread adoption of participatory modeling in many developing countries. In this study, a step-wise method to initialize the involvement of key stakeholders in the development of qualitative system dynamics models (*i.e.* causal loop diagrams) is presented. The proposed approach is designed to overcome the challenges of low expertise, time and financial resources that have hampered previous participatory modeling efforts in developing countries. The methodological framework was applied in a case study of soil salinity management in the Rechna Doab region of Pakistan, with a focus on the application of qualitative modeling through stakeholder-built causal loop diagrams to address soil salinity problems in the basin. Individual causal loop diagrams were developed by key stakeholder groups, following which an overall group causal loop diagram of the entire system was built based on the individual causal loop diagrams to form a holistic qualitative model of the whole system. The case study demonstrates the usefulness of the proposed approach, based on using causal loop diagrams in initiating stakeholder involvement in the participatory model building process. In addition, the results point to social-economic aspects of soil salinity that have not been considered by other modeling studies to date.

Key Words: Salinity Management; Stakeholder Participation; System Thinking; Causal Loop Diagram; Stakeholder Analysis; Participatory Modeling

3.1 Introduction

Soil salinity remains a very dynamic and challenging process to manage sustainably in the arid and semi-arid regions of the world. For example, on average, 14%, 20% and 26% of irrigated lands in Iran, India and Pakistan, respectively, are salt-affected (Shahid, 2013). An estimated 6 million hectares (Mha) of irrigated agricultural land in Pakistan, the focus area of this paper, is affected by soil salinity, causing a 62% loss in agricultural incomes (Tanwir *et al.* 2003). To solve the issue, the Pakistani government initiated a number of Salinity Control and Reclamation Projects (SCARPs) in the latter part of the 20th century; however, in 2000, further implementation was discontinued due to poor performance, high costs, and the short operational life of the associated infrastructure (Ghumman *et al.* 2012). The SCARP projects' demise resulted in weed growth in surface and subsurface drains, causing standing brackish water to accumulate on agricultural land. Such reclamation projects are usually designed based on the advice of local and foreign consultants, who in turn have based their advice on the results of physical modeling studies and site investigations. Some past physically-based soil salinity modeling studies in the area include LEACHM (Aslam and Van Dam, 1998), SALTMOD (Nasir *et al.* 2003), SWAP (Kuper, 1997; Qureshi *et al.* 2004; Sarwar *et al.* 2001) and UNSATCHEM (Condom *et al.* 1999). These studies, focusing only on the technical field-scale issues associated with soil salinity, recommended solutions without taking into account stakeholders in any meaningful way, or the social-economic aspects of the problem. This may result in the failure of policy decisions as observed in the SCARP case. Stakeholder participation is very important for successful policy decisions (e.g. Adamowski *et al.* 2013; Halbe *et al.* 2014; Medema *et al.* 2014a, Medema *et al.* 2014b); in fact, Nutt (2002) showed that 50% of policy decisions usually 'failed' because decision-makers did not include the knowledge and interests of key stakeholders.

Stakeholder involvement in environmental management and modeling has received very little attention to date in Pakistan. Small landholdings, the poor economic status of farmers, limited modeling and mathematical skills, and a lack of technical, political, and financial support have hampered the adoption of participatory modeling of soil salinity issues in Pakistan. Researchers have highlighted the need for joint action by governments, NGOs and farmers for salinity control and have advocated for the inclusion of stakeholders in all stages of soil salinity modeling and management (Tanwir *et al.* 2003). The modeling approach proposed in this paper is directly focused on addressing these types of problems regarding the initialization of stakeholder involvement in developing countries such as Pakistan.

The benefits of applying local, along with expert, knowledge in modeling exercises have been widely demonstrated in various research studies (*e.g.* Niazi *et al.* 2014; Halbe and Adamowski, 2011; Halbe *et al.* 2013; Langsdale *et al.* 2006). Meaningfully incorporating stakeholder contributions into the modeling process can help incorporate the ideas and knowledge of local key stakeholders, integrate physical and socio-economic components within a watershed or sub-watershed level, and improve model boundaries and completeness by ensuring that all relevant issues and views are addressed. Stakeholder engagement helps decision-makers take into account local realities, strengths, and constraints when developing appropriate policies and strategies, and can also reduce the level of conflict among stakeholders (Sterman, 2000). Stakeholder participation can also help garner support for the implementation of the most suitable strategies, as the involvement of local stakeholders in the development of these strategies creates a sense of 'ownership' and commitment to seeing the strategies successfully implemented (Pahl-Wostl *et al.* 2007; Straith *et al.* 2014).

The inclusion of stakeholders in water resources management has been advocated by many agencies in the water resources field (*e.g.* Global Water Partnership, European Union, International Water Management Institute) and frameworks (*e.g.* IWRM, adaptive management) as an integral component of sustainable water resources planning and management. However, to date, many organizations that are in charge of participatory watershed management have experienced significant challenges in finding effective and simple ways to, among other things, engage stakeholders in watershed modeling and management, especially in areas with low levels of expertise and funding, as is the case in many developing countries. Other significant challenges in participatory modeling are lack of stakeholder interest and unstable group composition. Burgin *et al.* (2013)], having conducted a study of stakeholder engagement in water policy in Australia, reported that more than half of the participants attended only one of twelve meetings. In another study, Videira *et al.* (2009) highlighted the issue of unstable group composition in a participatory river basin management modeling study carried out in Portugal. In addition, it is often difficult to capture individual stakeholder points of views or 'mental models' in group meetings since, for instance, some stakeholders might be reluctant to voice their opinions in the presence of government officials or their superiors in the organization.

The innovative modeling approach proposed in this paper, based on causal loop diagrams, (Mendoza and Prabhu, 2006; Sendzimir *et al.* 2007; Stave, 2002; Videira *et al.* 2009) directly focused on addressing these types of problems. The proposed approach is based on 'co-construction' participatory modeling that allows for the direct involvement of stakeholders with limited technical expertise, even in situations with limited financial and time availability, as is frequently the case in developing countries such as Pakistan.

The two main objectives of the research presented in this paper were to: (i) propose a step-wise and simple approach for engaging stakeholders in soil salinity management in developing countries under constraints of limited expertise, as well as financial and time resources, and (ii) explore the application of the proposed approach in Pakistan's Rechna Doab region. The proposed participatory modeling process can be categorized into four successive stages: (i) problem framing, (ii) stakeholder analysis, (iii) construction of individual causal loop diagrams (CLD), and (iv) construction of an overall group CLD (*i.e.* a CLD that includes all the views of the different stakeholder groups). The first stage describes the process of problem definition, which is crucial in the selection of stakeholders. The second stage involves the categorization of selected key stakeholders according to their roles and attributes. This type of analysis is important in prioritizing stakeholders according to their roles and importance. The third stage discusses the process of representing stakeholder views and ideas in the form of causal loop diagrams (CLDs), while the fourth stage involves the process of merging individual CLDs (mental models) into a final group CLD.

This research is particularly innovative since, to date, no attempt has been made to develop a simple and easily adoptable methodology to initialize stakeholder involvement in the development and use of qualitative causal loop diagram models with the aim of resolving agricultural water management issues (in this case soil salinization), applicable even in situations where stakeholders have minimal expertise, financial resources and time, as is often the case in many developing countries. A description of the proposed stepwise qualitative modeling process is provided in the following section.

3.2 Methodology

Stakeholder initialization and involvement in model development is a central issue in participatory modeling, and a variety of approaches, methods and guidelines exist to involve stakeholders in participatory modeling. Reed *et al.* (2009) and Reed (2008) provide a comprehensive review of different stakeholder engagement techniques. Normally, stakeholders are engaged through group meetings or interviews in a pre-defined form. The main problem with group meetings is the poor attendance of stakeholders; for example, not all of the participants might be interested in attending meetings. Stakeholders, particularly in developing countries, tend to have a lower interest in participating in group meetings compared to individual interviews (Burgin *et al.* 2013; Videira *et al.* 2009), as in the former case they may not be able to express their views openly due to the presence of 'opposing' groups or superiors in their organization. Another reason for the avoidance of centralized large-group meetings (*i.e.* those that require the traveling of stakeholders to a central meeting place) was that in studies addressing a large watershed area in developing countries, group meetings are usually not possible due to limited resources. As such, in the proposed approach, the facilitator travels to the stakeholders to guide the development of the individual CLDs.

The proposed approach in this study was developed so as to require less time and financial resources as well as mediation skills by omitting large group meetings (except for one large meeting when the overall group CLD is agreed upon). The overall process is illustrated in Figure 3.1, consisting of four main stages and seven steps: Stage i: problem definition (step 1); Stage ii: stakeholder analysis (step 2); Stage iii: stakeholder interviews (step 3) with construction of individual CLD models (step 4), which are later digitized using the Vensim software (step 5); Stage iv: construction of an overall group CLD (step 6) and the preparation of simple thematic models from the final merged CLD group model (step 7). The sections below describe each step in detail.

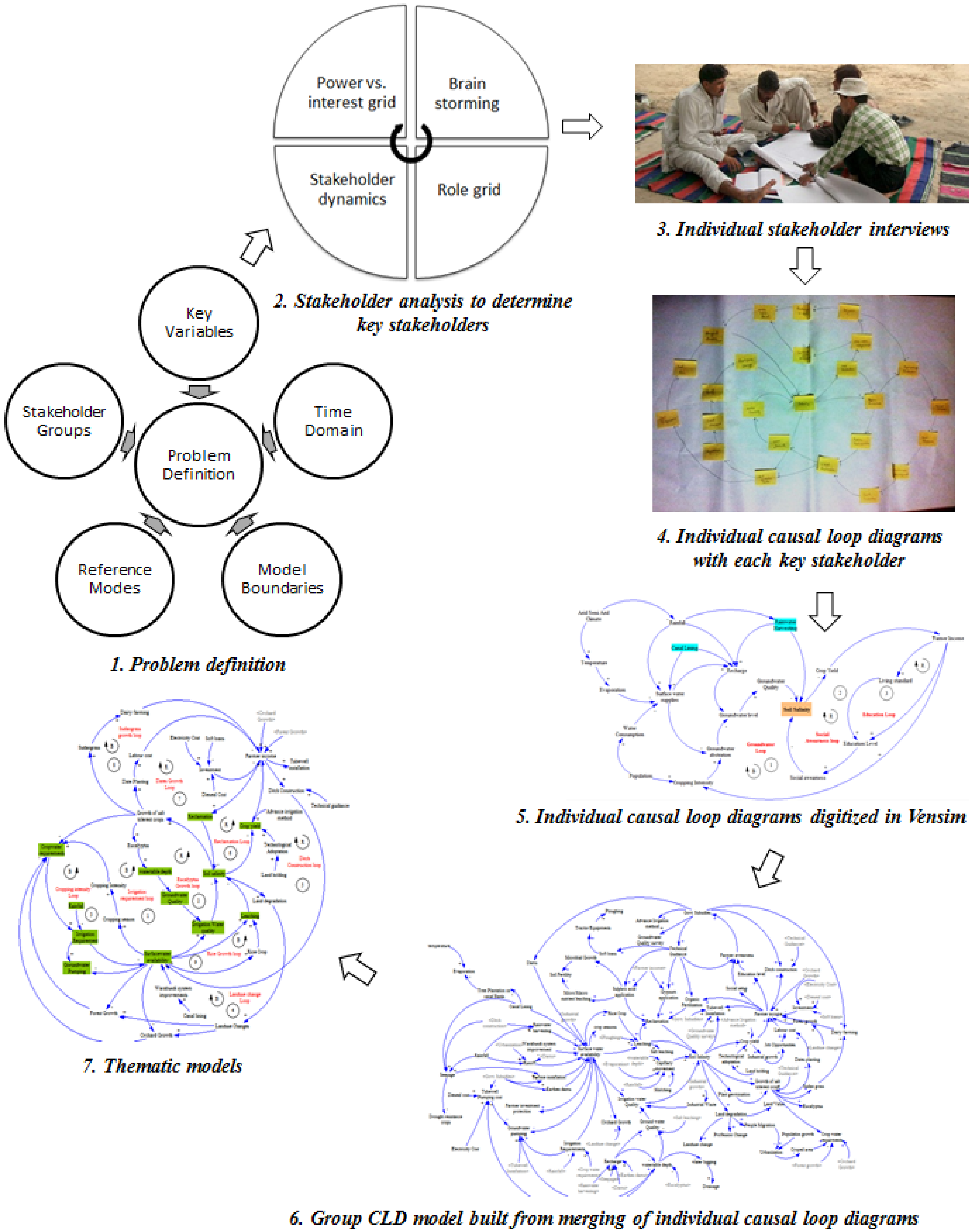


Figure 3.1. Qualitative CLD modeling process (main steps of the proposed approach)

3.2.1 Problem definition

Proper problem definition is important for the *stakeholder analysis* and *causal loop diagram* modeling phases of systems thinking and modeling. It is carried out by a facilitator (*e.g.* the first author of the case study explored in this paper) at the onset of the modeling process through initial discussions with local stakeholders regarding potential problems (*e.g.* the particular focus in this study was on soil salinity) that need to be addressed in a particular region, followed by a thorough literature review and analysis of the problem. While initially designed to cover a broad spectrum and thereby be inclusive of a wide range of stakeholders, the 'narrowing down' of the problem definition remains an iterative process achieved during subsequent, more focused, stakeholder engagement (described in the steps below). The success of the whole modeling process depends on a clear articulation of the problem that is to be studied and addressed via the proposed approach. While a clear articulation of the problem is particularly helpful in defining the purpose of the model, its boundaries and time domain, it also affects the selection of stakeholders in the modeling process. Care is taken to link the problem definition step to stakeholders' needs, capabilities and skills to maintain their motivation and commitment (Sterman, 2000). The five main stages in problem definition are: (i) selection of the problem theme and key variables, (ii) selection of the time horizon, (iii) definition of model boundaries, and (iv) development of reference modes (*i.e.* a graphical representation of change in the problem over time) to represent the dynamic behavior of the problem and (v) identification of stakeholder groups. Reference modes can be helpful in detecting the variables most indicative of the evolution of the situation (Videira *et al.* 2009). The problem definition is an iterative process; after stakeholder analysis (see below), the problem definition can be modified (and even completely changed if the key stakeholders think that this is necessary).

3.2.2 Stakeholder analysis

Once the general problem to be addressed is selected, it is necessary to identify which key stakeholders should be involved in the modeling process. Stakeholder analysis is the process of selecting and categorizing the stakeholders on the basis of their role, interest, power, legitimacy, and urgency. Stakeholder analysis aims to evaluate and understand the stakeholders' relevance to a project or policy (Mitchell *et al.* 1997). Bryson (2004) provides a comprehensive review of different stakeholder analysis techniques. In the current study, a widely tested framework, developed and applied by Elias *et al.* (2002) in different case studies, is used. This framework combines the widely used stakeholder analysis technique developed by Freeman (2010) and that of Mitchell *et al.* (1997), rendering the resulting framework more complete, inclusive and versatile than other approaches. The framework consists of four major steps: (i) a listing of stakeholders, including marginal ones, achieved through brainstorming; (ii) their categorization on the basis of their roles; (iii) their prioritization according to their attributes; and (iv) their selection on the basis of their power and interest.

The brainstorming process can be supported by secondary sources (*e.g.* academic literature, reports and the knowledge of facilitators). One effective approach, as suggested by Brugha and Varvasovszky (2000), is to start with a group of stakeholders predefined through a literature survey or local knowledge and to ask them to identify other stakeholders. Brainstorming is, by nature, a divergent process and involves even apparently marginal stakeholders. This stage is iterative in nature and the preliminary list, created in the first step, can be amended during the interview stage of stakeholders upon identification of other individuals or groups. After the list is finalized, details about their roles and group associations can be established.

The list of stakeholders is further categorized according to stakeholder roles. In the current study, the European Commission (2003) criterion is followed to identify four major categories of stakeholder roles with respect to resource issues: decision makers, users, implementers and experts. Assigning different roles to stakeholders is helpful in finding gaps in the first brainstorming step and in looking for omitted relevant parties.

The participation of stakeholders can change over time. New stakeholders may join and old ones may leave the system over the time span of the modeling process. Stakeholder interest may also change over time due to changes in the system state or in strategic issues, and this must be taken into account in the process. In the current study, a comprehensive methodology of stakeholder dynamics developed by Mitchell *et al.* (1997), which classifies stakeholders on the bases of three relationship attributes (power, legitimacy and urgency), is followed. During the process, stakeholders' attributes may evolve over time, thereby increasing or decreasing their importance according to whether they have acquired or lost one or more attributes. Finally, a power *vs.* interest grid (Crosby and Bryson, 2005) is used to complement the approach of Mitchell *et al.* (1997)].

The final composition of the stakeholders should involve representation of all roles (*i.e.*

decision makers, users, implementers and experts), as well as stakeholders who are related to at least one of the attributes of power, legitimacy, urgency, and interest.

3.2.3 Stakeholder interviews with construction of individual causal loop diagrams

After the completion of stakeholder analysis, potential stakeholders were contacted, and individual interviews were conducted to build causal loop diagrams which record their views on the problem being explored. Causal loop diagrams (CLD) are an excellent way of capturing the views and ideas of stakeholders within a model structure (see Figure 3.2). CLDs have been successfully used in water resources planning, policy analysis, sustainable development and natural resource management (Dai *et al.* 2012; Prodanovic and Simonovic, 2007; Sendzimir *et al.* 2007).

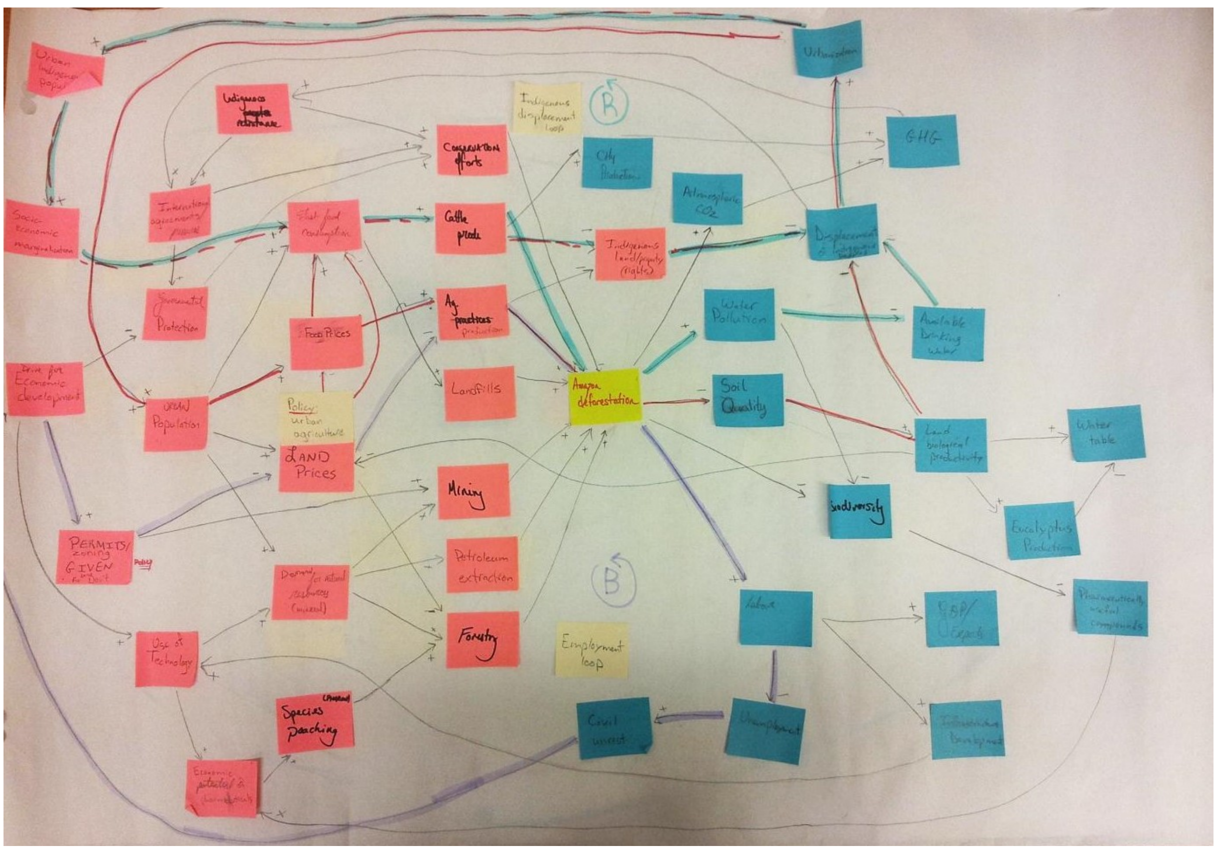


Figure 3.2. Causal loop diagram developed during a stakeholder interview. Note: fluorescent yellow sticky note = problem variable; pink sticky notes = causes of problem; blue sticky notes = consequences of problem; light yellow sticky notes = policies/strategies to address problem

CLDs are powerful tools for the qualitative analysis of systems. They aid in depicting a system's structure and also mark time delays that are often responsible for difficulties in controlling inherent dynamics. In these diagrams, elements of the system are connected by arrows that link cause and effect variables together to form causal chains. A positive link indicates parallel behavior of variables: in the case of an increase in the causative variable, the effect variable also increases, while a decrease in the causative variable implies a decrease in the affected variable. Alternatively, a negative link indicates an inverse linkage between the variables. Closed circles or loops are important in understanding CLDs. They may be either reinforcing or balancing loop. A reinforcing loop is a cycle in which the effect of a variation in any variable propagates through the loop and returns to the variable reinforcing the initial deviation while a balancing loop is the cycle in which the effect of a variation in any variable propagates through the loop and returns to the variable a deviation opposite to the initial one.

Interviews with each stakeholder were conducted in order to help each stakeholder build their own CLDs. The four steps described by Vennix (1996) were followed to develop the CLDs. Readers are encouraged to read the details of the four-step process followed by referring to Vennix (1996). A stakeholder (*e.g.* a local farmer) is first presented with the purpose, objective and method of drawing a causal loop diagram through a simple example. Colored sticky notes and large plain paper sheets are provided to the stakeholder to create their mental model. First, the stakeholder affixes the problem variable in the middle of the sheet; then, the stakeholder is asked to add causes (direct or first-order causes first, and indirect or second-order causes second, and so on) on the left side of the problem variable, using sticky notes. In the next step, causes are joined through causal links, and polarities and directional arrows are added (in pencil). Direct and indirect consequences (or first-order and second-order consequences, etc.) are then added on the right side of problem variable. Similarly, causal links with polarities are defined between the consequences. Finally, causes and consequences are joined through feedback loops. Figure 3.2 shows the initial causal loop diagram of an individual stakeholder (a local farmer in this case) from an actual group model building exercise conducted by the authors.

The following types of questions are asked during the interview to help each stakeholder in developing their individual causal loop diagram:

1. How has the problem developed over time?
2. What are the main direct and indirect causes of the problem's development, including link polarities?

3. What are the consequences of the problem?
4. What are main feedback processes?
5. What kind of short-term policies do you think can be adopted to solve this problem?
6. What kind of long-term polices can be adopted to solve this problem?
7. What are the main hurdles in the success of these policies?

Based on the information received from the stakeholders, the time horizon and the boundaries of the problem definition are refined. In addition, the list of potential stakeholders developed during the stakeholder analysis step is discussed with the stakeholder-interviewee to identify any missing stakeholder groups or individuals.

Depending on the availability of a particular stakeholder, one of three interview options is adopted. When time is limited (*e.g.* 15 min), the interview is recorded and later translated into a CLD by the facilitator. The causal loop diagram is sent to the interviewee afterward for them to approve whether the diagram represents his or her point of view. Where the interviewee's availability is slightly longer (*e.g.* 30 min), a preliminary diagram (based on literature and other stakeholder interviews) is prepared and stakeholders are asked to correct the diagram or to append further causes and consequences to it. If a stakeholder has enough time (*e.g.* greater than one hour), the modeling exercise is started from scratch. During the interviews, stakeholders express their views regarding the problem, its causes, its consequences, feedback loops and possible strategies and policies to address the problem, using causal loop diagrams. All policy options are included in the diagram as policy variables. Important loops are numbered and labeled on the basis of their reinforcing or balancing behavior. Furthermore, for the purpose of quick reference, the loops are named according to the process they represent (*e.g.* groundwater loop, social awareness loop, etc.). After each stakeholder interview process is complete (*i.e.* after a stakeholder has built their CLD), a widely-accepted tool for system dynamics modeling studies, Vensim DSS, is used by the facilitator to translate all the paper CLD models into a computer modeling environment.

3.2.4 Construction of an overall group CLD

Following the development of each of the individual stakeholder CLD models, a preliminary group CLD model is built by the facilitator by analyzing, comparing, and merging all individual casual loop diagrams. The initial group CLD is later discussed in detail in a follow-up stakeholder group meeting (which can last from several hours to a full day) to finalize the overall group CLD. The merged model is aimed at representing the different views and mental models/maps of all the different stakeholders regarding the problem, its causes, its consequences, feedback loops and possible strategies and policies to address the problem along with their preferred strategies (*e.g.* in this case study, strategies to address soil salinity in the basin). This allows for the highlighting of the perspectives of different stakeholders and for developing an overall mental map of the system.

When choosing which individual stakeholder's model to start to build upon when developing the overall group model, the most comprehensive model is generally used, and variables from the other stakeholders' models are then added. Figure 3.3 explains the merging process by taking the example of two stakeholder-built models (denoted as "Model I" and "Model II"). The process begins with the most comprehensive model, and continues until all the complementary, redundant and controversial elements have been addressed in the overall CLD. The whole merging process can be divided into six categories (Figure 3.3):

(i) If there is good agreement between two stakeholder-built models (Column 1), *i.e.*, both agreed that variable 'A' has the same influence on variable 'B', then in the merged model variable 'A' is causally linked with variable 'B'.

(ii) If the first stakeholder thinks process 'A' will affect process 'B,' while the second stakeholder thinks the opposite (Column 2), then both links are incorporated in the merged diagram, but tagged with an exclamation sign as a controversy.

(iii) If the first stakeholder thinks consequence variables 'B' and 'C' of variable 'A' are causally linked, whereas the second stakeholder believes them to be conditionally independent, then the opinion of the first stakeholder is included in the merged model, but tagged with a question mark as a controversy of type II (Column 3).

(iv) If the first stakeholder believes variable 'A' affects both 'B' and 'C,' whereas the second stakeholder believes 'A' to only affect 'B,' but not 'C', then this type of controversy is incorporated by tagging the causal link between 'A' and 'C' with a question mark as a controversy of type III (Column 4).

(v) If the first stakeholder (or stakeholder group) believes variable 'A' influences 'B', and the second group thinks it may affect 'C' also, then the mental modes of both stakeholder groups are incorporated in the merged CLD by adding an additional causal link to variable 'A' (Column 5).

(vi) In the case of redundant elements, such as when mental models "I" and "II" represent the same causal link between variable 'A' and 'C', but with different levels of detailedness, the opinion of the first stakeholder group with more detail is included in the merged model (Column 6).

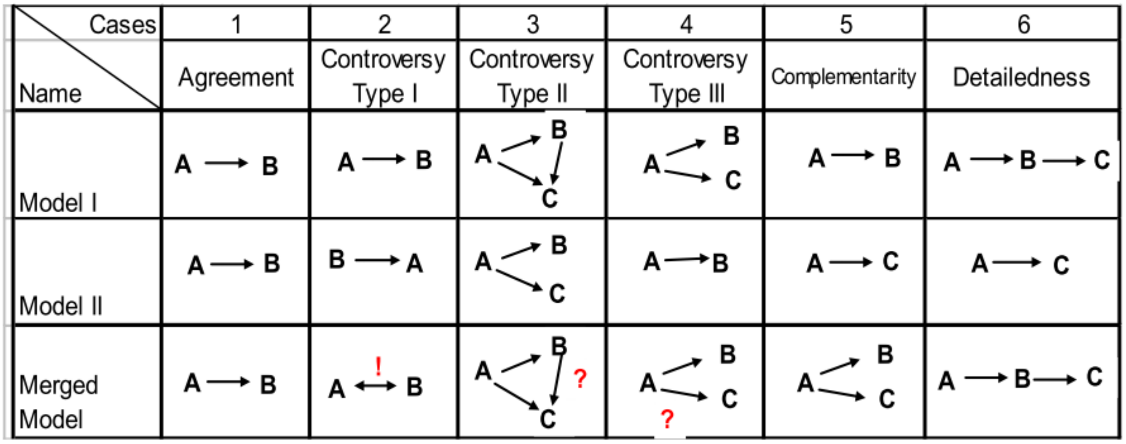


Figure 3.3. Marking different perceptions in a merged causal loop diagram

The resulting final merged CLD model includes the diverging perspectives of stakeholders. The merged group causal loop diagram is helpful in describing the qualitative behavior of the system through its different reinforcing and balancing loops. This type of qualitative analysis cannot be used to infer quantitative behavior but serves a number of useful purposes, including detecting the system's critical issues, identifying knowledge gaps for further research, increasing stakeholders' understanding of a complex ecological and socio-economic system, finding conflicts of interest, and facilitating decisions regarding long-term policy analysis. Merging individual models from a number of stakeholders may increase model details to the point where sub-models on different aspects can be identified. Hence, it is advisable to split the merged group CLD model into different thematic models (*e.g.* industrial growth, agricultural management) on the basis of environmental, social and physical aspects. It should be noted that the thematic models are all linked to form the overall group CLD. The practical application of the proposed approach is discussed in the following section through a case study completed by the authors in Pakistan's Rechna Doab region.

3.3 Description of the study area

The approach developed for the initiation of stakeholder engagement via CLDs was tested in a case study undertaken in Pakistan's irrigated region of Rechna Doab. The study site is in the Rechna 'doab' (land between two rivers) region, located in the downstream portion of the Ravi and Chenab rivers' inter-fluvial basin (*i.e.* just above the intersection of the two rivers) in Pakistan.

Covering roughly 732.50 km^2, the basin is situated within the Haveli canal command. Potentially cultivatable land, presently unexploited due to high soil salinity levels, makes up 30% of the area. Despite significant expenditures on fertilizer inputs, the Haveli subdivision is plagued with much lower returns than neighboring subdivisions (Rehman *et al.* 1997b). The mean area of the region's landholdings is 3.85 ha (Kiani, 2008). The area is situated in the agro-climatic zones of the Punjab, where rice-wheat [*Oryza sativa* L. - *Triticum æstivum* L.] and cotton-sugarcane-cotton [*Gossypium hirsutum* L. - *Saccharum officinarum* L.] rotations are common. Cotton ginning and sugar production are the main industries of the area. The study area portion of the Rechna Doab basin is shown in Figure 3.4.

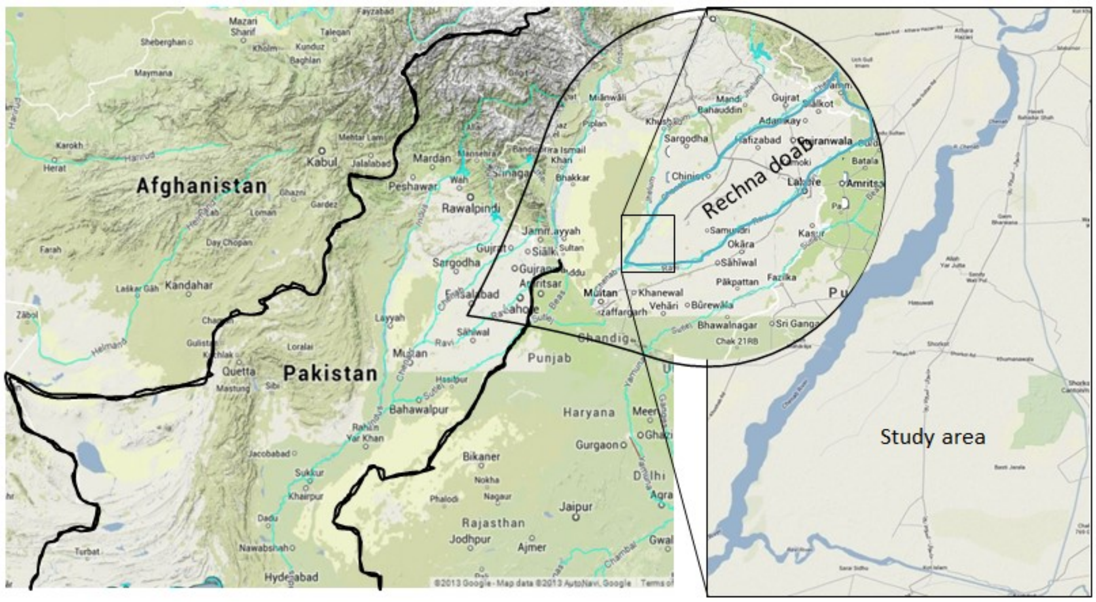


Figure 3.4. Study area in the Rechna Doab basin, Pakistan

Due to the scarcity of the surface water supply, 75% of farmers use groundwater of marginal quality for irrigating their crops (Rehman *et al.* 1997a, b, c, d, e). Groundwater depth varies from 3 to 6 m, with groundwater electrolyte concentrations exceeding 1500 ppm in the middle portion of the basin (IWASRI, 2005). While the use of marginal-quality groundwater creates the problem of secondary salinization in the area, this area could potentially be reclaimed by good management practices and better policies. According to estimates, 26.2% of Pakistan's total irrigated area is salt-affected, but nearly 70% of the salt-affected area is only moderately saline and can potentially be reclaimed (Kazmi *et al.* 2012).

The Haveli internal command area of the Rechna Doab basin in Pakistan was selected for the case study based on the fact that:

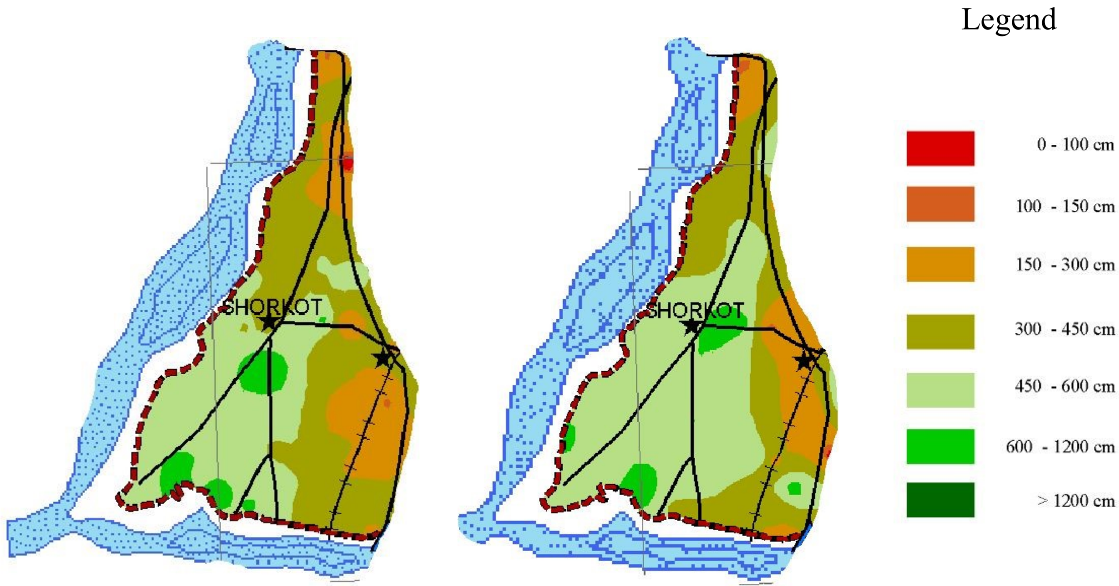
1. It lies on the downstream side of a canal command operating under arid climatic conditions. While soil salinity problems exist under the conditions characteristic of this particular region, the principles and policies developed in this case study can be applied to other areas in Pakistan and elsewhere, where similar conditions prevail.
2. It is bounded by two rivers, providing good hydrological/boundary conditions for the modeling exercise.
3. It is a region that has a large amount of field-recorded data. Various organizations (*e.g.* WAPDA, Irrigation Department and Soil Survey of Pakistan) have actively been monitoring water table depths, water quality and soil salinity since the early 1960s. In addition, a number of previous research studies have been conducted in the area (IWASRI, 2005; Jehangir and Ali, 1997; REC, 1978; Rehman *et al.* 1997a, b, c, d, e; SMO, 1987; Van Dam and Aslam, 1997; WAPDA, 1978). All of this archival research and data can be used for stakeholder analysis, as well as in developing a reference mode for the system dynamics modeling study.
4. Farmer organizations and NGOs are active in this area, which facilitates their participation in the qualitative modeling exercise.

3.4 Results

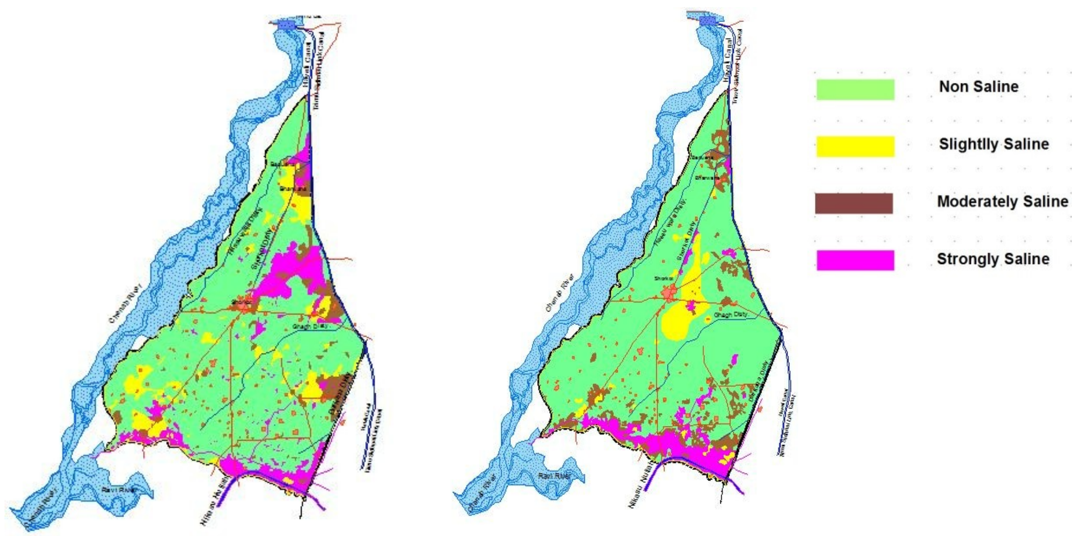
The case study research in the Rechna Doab Basin, Pakistan was conducted to examine the problem of secondary salinization with stakeholders on a sub-watershed scale. The overall process took five months to complete. Overall, it was found that the proposed approach was very cost-effective i.e. it required least resources (e.g. one large sheet of paper, pencil, eraser, highlighter and some sticky notes) and required little technical expertise and time from stakeholders, making the approach very useful in a developing country context. All interviewees were able to understand and apply the method after a short introduction of 30 min. This training was sufficient for the participating stakeholders to make their own CLD models. The applications of the different stages of the proposed approach are described in detail in the following sections.

3.4.1 Stage 1. Problem definition

Based on a detailed literature review conducted by the authors, in addition to expert and stakeholder consultation, the significant increase in soil salinity in the study area was determined to be a critical problem that needed to be addressed via stakeholder engagement. To meet the challenges of waterlogging, the Pakistani government encourages the installation of tubewells. Government subsidies have incited farmers to increase cropping intensities, using the installation of a large number of private tubewells to supply sufficient groundwater. In the last three decades, a 470% increase in tubewell growth over Punjab, Pakistan was observed. These tubewells presently supply more than 50% of farm irrigation water (Qureshi *et al.* 2004) in Punjab. This large increase in tubewells has resulted in both declining groundwater tables (Figure 3.5) and deteriorating groundwater quality; the groundwater quality in the middle portion of the study watershed is hazardous, with electrolyte concentrations exceeding 1500 ppm (IWASRI, 2005). Farmers have continued the practice of using marginal-quality groundwater, which results in problems of secondary salinization. Surveys undertaken in the 1970s by the Water and Power Development Authority (WAPDA), and the Soil Reconnaissance Survey of Pakistan, confirmed the imminent threat of salinization arising from the use of poor quality groundwater. Figure 3.5 shows the change in soil salinity over a period of two decades; the classification is on the basis of USDA criteria [EC < 4 dS m^{-1} (non-saline), EC = 4-8 dS m^{-1} (slightly saline), EC = 8-16 dS m^{-1} (moderately saline), EC > 16 dS m^{-1} (strongly saline)] (L. A. Richards, 1954). The lessons learned from the failure of SCARPs have highlighted the fact that surface salinity is a highly dynamic process (Metternicht and Zinck, 2003) that is closely tied to human interventions.



Water table depth 2000 2002



Soil surface salinity 1981 2003

Figure 3.5. Change in water table depth and soil salinity in the study area over time (IWASRI, 2005)

During the interview phase of the modeling study (individual CLD development with each stakeholder), the soil problem variable preliminarily considered (*i.e.* soil salinity) was confirmed by stakeholders to be the area's critical problem (see section 3.4.3).

3.4.2 Stage 2. Stakeholder analysis

Following the problem definition stage, a list of stakeholders was created through a brainstorming process (including 'marginal' stakeholders at this point). The literature review and expert opinion showed the WAPDA and the Provincial Irrigation Department to be two important stakeholders. The WAPDA is mainly involved in the control of irrigation water releases from dams, whereas its subdivisions, the International Waterlogging and Salinity Research Institute (IWASRI) and the Soil Monitoring Organization (SMO), implement, respectively (i) soil salinity control projects, and (ii) monitoring of groundwater levels, along with the qualitative and quantitative evolution of groundwater salinity status.

The Provincial Irrigation Department, together with the local water board, the farmers' organization, and the water user's association, are responsible for the provision of irrigation supplies at farm outlets, and were included in the initial list of stakeholders. The Department of Agricultural Engineering in the Department of Agriculture was found to be another important stakeholder with its sub-departments of tubewell drilling, water management and farm machinery. Other important stakeholders were the Soil Salinity Research Institute, Land Reclamation Department, watershed research organizations, local farmers, industry, tourism, agribusiness, local governments and consultants.

In the next step, based on the framework developed by the European Commission (2003), stakeholders were categorized as experts, decision-makers, implementers, or users in order to assess missing links (see Appendix 3A). At this stage, sorted stakeholders were contacted and requested to give their suggestions about any missing and possible future stakeholders. The majority of stakeholders contacted were satisfied with the list, but suggested adding non-governmental organizations (NGOs) locally involved in carrying out rural support programs for farmer awareness and social welfare. As part of a UN grant, one NGO was initiating a project of land rehabilitation (a Bio Saline project), by providing gypsum to local farmers at a subsidized rate. The majority of stakeholders suggested excluding the tourism industry from the list as it was not a significant stakeholder/player in the area. As such, the tourism industry was excluded, and an NGO was added to the preliminary stakeholder list.

The assessment of stakeholder dynamics was carried out by using the approach developed by Mitchell *et al.* (1997). In the case study, stakeholder dynamics revealed the possibility of a future participation by the industrial sector. The industrial representative showed the least interest in the study, because this sector grows its crops on its own farms on fertile land. However, in the future the industrial sector may also fall victim to the continued deterioration of groundwater quality and non-availability of surface water. Another sector which may be affected in the future is the domestic sector. The final outcome of the stakeholder typology analysis is illustrated in Appendix 3B.

In addition, a power vs. interest grid approach developed by Crosby and Bryson (2005) was completed to prioritize stakeholders (see Appendix 3C). The WAPDA, the Ministry of Agriculture and Livestock, Farmer Organizations, the Water Management Department and area water boards were considered to be the most powerful parties with respect to the management of soil salinity in the case study area.

Finally, on the basis of the stakeholder roles, their dynamics, the power *vs*. interest diagram, and stakeholder recommendations, the WAPDA (its sub-departments IWASRI and the Soil Monitoring Organization), the Irrigation Department, Farmers' Organizations (FOs), local farmers, the Water Management Department, industries, NGOs (Bio Saline project), the Agriculture Department, the Land Reclamation Department, and the Soil Salinity Research Institute were included in the individual CLD modeling process.

3.4.3 Stage 3. Stakeholder interviews and individual causal loop diagram preparation

After the selection of potential stakeholders (described in section 3.4.2), these stakeholders were contacted for interviews to develop the individual CLDs. After a 30-min introduction to the process of building causal loop diagrams (CLDs) through an example model, the stakeholders became comfortable with the exercise and built their own CLD models. The first author acted as the facilitator for the development of CLD models. This involved meeting the different stakeholders in different parts of the study area over the course of 8 weeks. The stakeholders showed confidence in the modeling exercise and were satisfied with their causal loop diagrams and how they fully represented their mental maps in the form of causal links.

Individual CLD modeling with each stakeholder began with the problem variable. When stakeholders in the study area were initially asked to point out the main problem to which they attributed their lands' low production, the majority pointed to soil salinity, while others coupled soil salinity with low availability of irrigation water, or inequitable distribution of canal water. All stakeholders held the view that the problem could be solved if good quality water became available in sufficient quantities. The next step involved adding direct and indirect causes of soil salinity in the area, for which different stakeholders were seen to express different perspectives. The primary cause of soil salinity was generally cited as tubewell irrigation with marginal-quality groundwater, though in some locations a saline parent material due to the weathering of different rocks (which are rich in salt content) was also closely associated with the problem. Some stakeholders pointed out the historical operations of SCARP tubewells in the area as the major cause. They believed that inadequate drainage capacity had disturbed the salt balance in the area. This opinion was not shared by some other stakeholders, who argued that during the monsoon season their land became flooded with excess water and all these salts should have already been leached out. They considered the continued use of marginal-quality tubewell water as the major cause of unproductive lands. Some stakeholders pointed to the disposal of sugar mill wastes on productive lands as a major cause, but others considered it a source of fertilization. This aspect needs further investigation, but given the small area affected by this waste, it was not considered a significant variable in this particular study.

The next stage in the CLD building process was the addition of the different consequences of soil salinity. Different direct and indirect consequences were added until stakeholders were satisfied with the model. The added consequences represented what the stakeholders considered important in terms of social, economic and environmental issues. The flexibility of the system dynamics modeling approach allowed for the inclusion of different kinds of variables, which is one of the main strengths of this approach. Major consequences included decreases in crop yield, land degradation, and growth of salt tolerant-crops. In the final stage the developed model structure was analyzed for any feedback relationships between the causes and consequences.

Figure 3.6 provides a simplified example of two different policies (*i.e.* investing subsidies in tubewell installation or in canal lining) with the basic steps that were used by the stakeholders to develop the individual causal loop diagrams in this study. In this example, soil salinity is first marked as the problem variable. Capillary movement and the water table depth are marked as direct and indirect causes, followed by the addition of government subsidies, tubewell installation, canal lining and groundwater pumping as direct and indirect consequences. Linking groundwater pumping with water table depth represents the feedback loop between the causes and consequences. Two different polices for controlling water table depths are represented by reinforcing and balancing loops. In the first case (*i.e.* the balancing feedback loop - the 'groundwater pumping loop' - indicated in red in the figure 3.6), the main focus is on investing government subsidies in tubewell installation, which in turn reinforces the effect of groundwater pumping, thereby increasing water table depth from the soil surface. This highlights the policy adopted by the government in the SCRAP V project, when the main cause of soil salinity was due to shallow water table conditions. An alternative government policy is represented by the reinforcing 'canal lining loop'. With this policy, the government invests in subsidizing canal lining. This discourages groundwater pumping due to improved canal supplies, and thus improves water table depth with an increase in capillary movement.

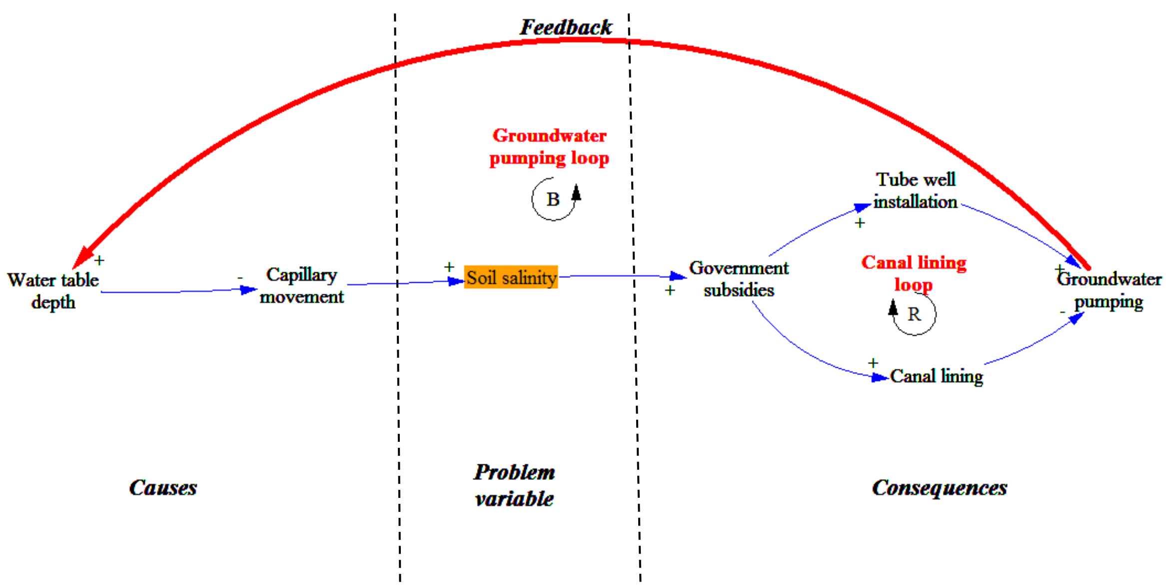


Figure 3.6. Casual loop diagram drawing procedure with balancing and reinforcing loops

Each stakeholder prepared their causal loop diagram independently. During the entire process the facilitator helped with procedural issues only, remaining neutral in order to avoid any sort of influences or biases. Once their views (in the form of causes, consequences, feedback loops, etc.) were expressed in the causal loop diagram, stakeholders were asked by the facilitator: "What kind of policies do you think would be effective in the mitigation of the soil salinity problem?" All research institute and departmental personnel praised government policies regarding canal lining, stating that considerable quantities of water which would no longer be lost to seepage could be effectively used in downstream regions to reclaim irrigated land. On the other hand, farmers strongly criticized the government policy of canal lining in the area, as they believed that this lining, instead of improving surface water supplies, reduced groundwater seepage, thereby causing further deterioration in groundwater quality. Others thought that removal of trees from canal banks for lining purposes would increase surface water evaporation losses and that no additional water would reach downstream users. As this situation required further analysis through modeling exercises, both options were included in the merged model diagram. Based on stakeholder recommendations, canal lining is marked as a policy variable. Assessing canal-lining policies through quantified model simulation constitutes one of the next stages of this research, which will be addressed in a future paper.

All stakeholders found Sudan grass [*Sorghum* × *drummondi* (Steud.) Millsp. and Chase] to be the most viable crop option for saline lands. As a salt-tolerant plant, Sudan grass not only removes salts from the soil root zone but can also be used as feed on dairy farms in the area. Some stakeholders highlighted the need for technical support and soft loans from the government for rainwater harvesting. They felt that in the flooding season there is more than enough water to be used if it was stored for future use. They believed that with government support in the form of soft loans they could construct earthen ponds and use flood/rainwater to reclaim their lands. Recharge wells and installation of turbines on canal banks were identified as short-term policies, while construction of large-capacity dams was considered a viable long-term policy for soil salinity control.

3.4.3.1 Causal loop diagram merging

Following the individual CLD modeling process, individual CLDs were merged by the first author who played the role of facilitator during the individual CLD-building exercises. Merging (see section 3.2.4) gives rise to a holistic view of the complete system, as is illustrated in Appendix 3D, where an example of the merging of two stakeholder-built models is portrayed. The merging process began with the most comprehensive model, with additional variables being incorporated until the views of all stakeholders were taken into account. All controversies and conflicting ideas were indicated in the merged diagram (for future discussions with all stakeholders present together). As part of the finalization of the merging process, stakeholders attended one follow-up meeting, where wide-ranging discussions sought out their opinions on the merged CLD, controversies, etc. This process also allowed for the sharing of one group's ideas with those of the others.

The preliminary merged diagram (*i.e.* the overall CLD) (see Figure 3.7) was presented to stakeholders to elicit their opinion regarding the overall model (and process). After some minor changes, all stakeholders indicated their satisfaction with the modeling process and the overall group CLD model. They were surprised about the transparency of the process and very enthusiastic as to how well they were able to depict the aspects of a complex system in a clear, simple and understandable way. Others liked the way different controversies were highlighted, and how discussions aimed at solving these controversies were structured around a CLD model that they had built and therefore understood. According to one group it was “a wonderful way of consensus-building which should be applied to other issues in the environmental field, for social learning and in seeing the bigger picture in the face of a given problem.”

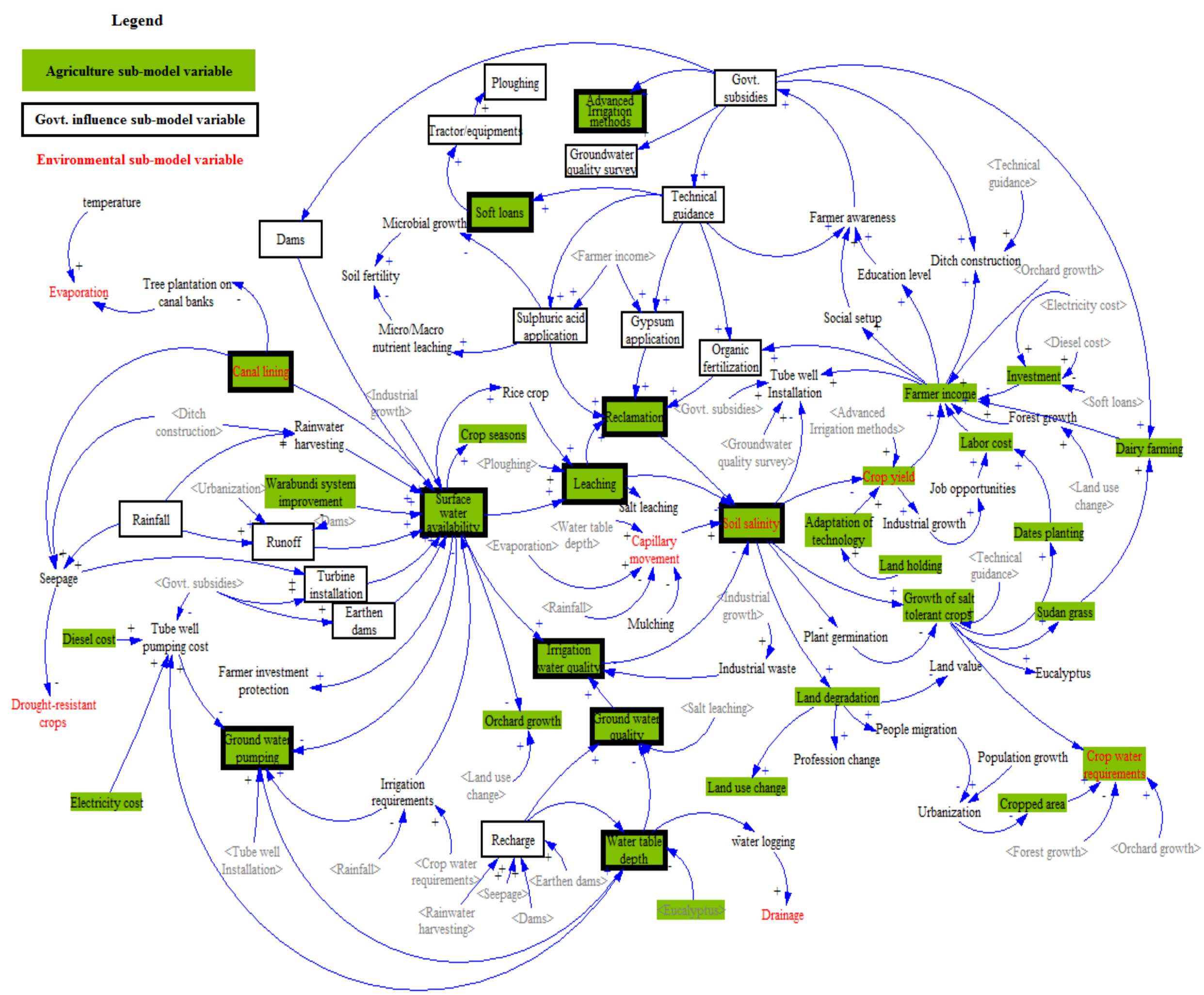


Figure 3.7. Final merged causal loop diagram of all eleven CLDs from the different stakeholders

3.4.3.2 Thematic model development

The next step (completed by the facilitator) was to divide the large merged CLD into different thematic sub-models addressing agricultural, social, environmental, and economic components of the overall system. This kind of division helps in evaluating the details of different aspects in isolation from other factors, and also simplifies the model structure for future quantification purposes (*e.g.* the agricultural sub-model deals with agricultural process variables only, with similar units, whereas the sub-models of the social system deal with the change in education levels, migration, and industrialization parameters with entirely different techniques of quantification and units). It should be noted that the thematic models are all still connected through common variables. The various environmental sub-models (*e.g.* irrigation and groundwater quality, wastewater production) represent the change in environmental conditions due to soil salinity, while economic sub-models deal with government preferences in terms of government subsidies for canal lining and advanced irrigation techniques.

As an example, Figure 3.8 shows the inclusion of sub-processes in thematic models. For example, for the agriculture thematic model, farmer income, groundwater, water availability, reclamation and land use/crop rotation processes were included (Appendix 3E). Amongst the four thematic models, the agriculture model is selected for discussion purposes as it covers an important physical process that governs the dynamics of the local soil salinity process in the Rechna Doab, Pakistan.

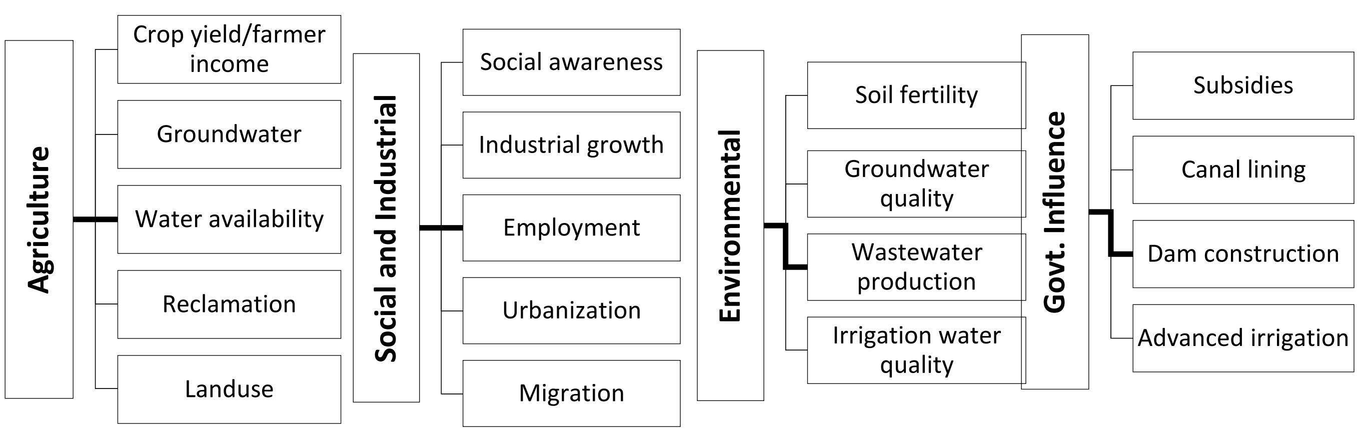


Figure 3.8. Merged thematic models with their sub-modeling processes

3.4.4 Qualitative analysis of agriculture thematic model

The agriculture thematic model consists of 9 major loops (Figure 3.9) covering five sub-processes of crop yield, groundwater, water availability, reclamation and land use (Figure 3.8).

Loop 1 (Irrigation requirement loop) shows the balancing effect of soil salinity on irrigation water requirements. An increase in soil salinity promotes the growth of salt-tolerant crops, which causes a reduction in crop water requirements, thereby increasing surface water supplies by reducing irrigation water requirements. The additional available water, in addition to improving irrigation water quality, leaches down excessive salts, thus reducing soil salinity. On the other hand, an increase in surface water availability increases cropping seasons and cropping intensity, thereby leaving no water for soil reclamation (Figure 3.9, loop 3, cropping intensity loop).

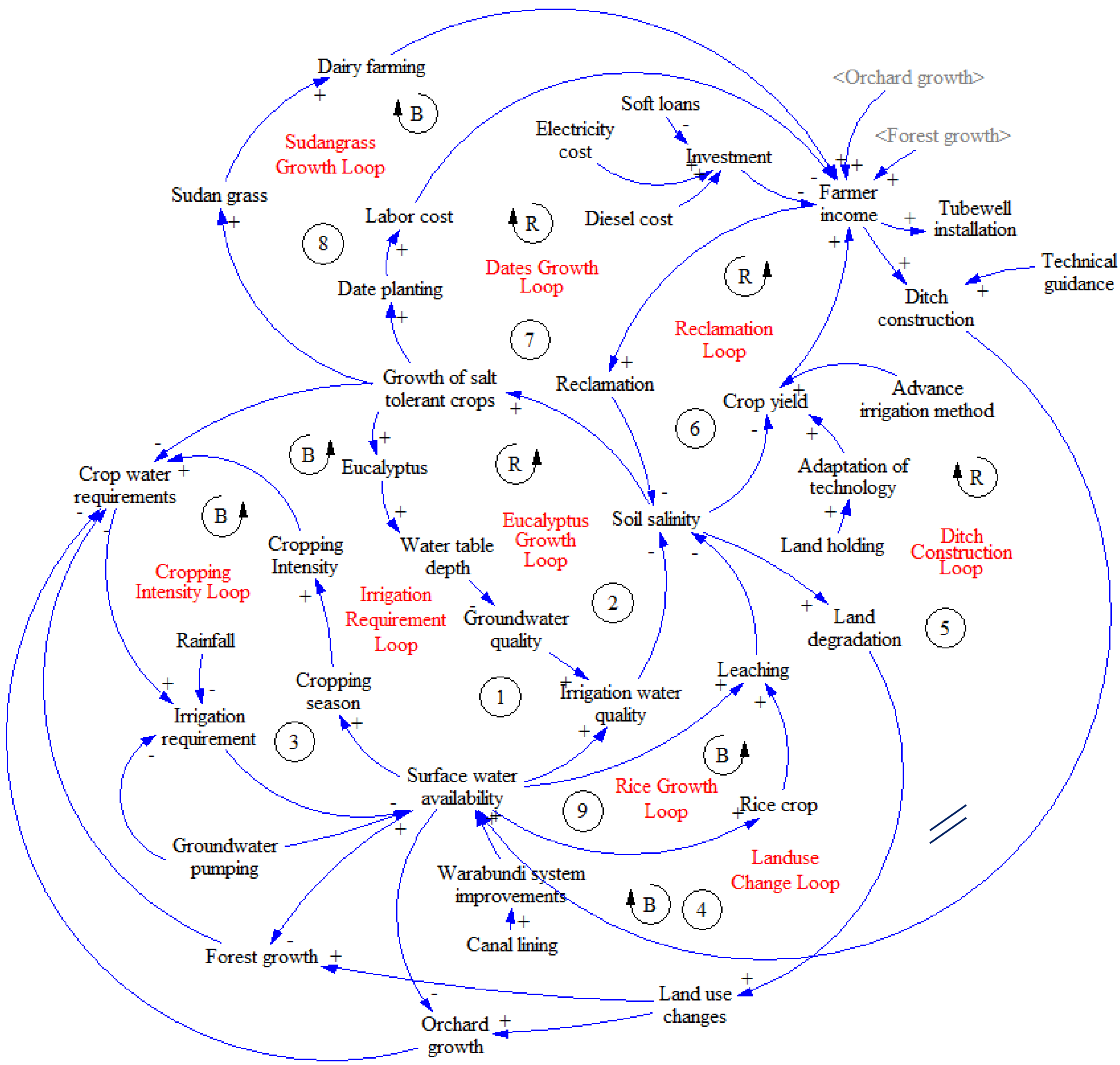


Figure 3.9. Digitized merged agriculture thematic model in the Vensim software environment

This type of behavior represents competition between two types of crop, *i.e.*, a salt tolerant crop and agronomic crops. The system's real behavior can be represented by the interplay of these two loops, the dominance of one loop over the other controlling surface water availability. Shortage of surface water supplies can degrade fertile land and lead to a change in land use (Figure 3.9, loop 4, land use change loop). Soil salinity and land use is incorporated with time delay functions, whereas changes in land values are not considered due to their wide variation and the role of real estate therein. On degraded lands, farmers can adopt the option of forest or orchard growth, and by so doing can cause a significant positive effect on farmer income.

This increase in income through crop yield or orchard production can help farmers construct earthen ditches for rainwater harvesting and flood control (Figure 3.9, loop 5, ditch construction loop). Rainwater harvesting and a flood storage strategy would yield benefits in terms of assured surface water availability, reduced groundwater pumping, and improved recharge. Another option for increasing surface water availability is canal lining (see Figure 3.9, where surface water availability is represented as a function of canal lining and ditch construction in the agriculture thematic model, as seen from the causal links). Increased surface water supply can promote the growth of rice crops (Figure 3.9, loop 9, rice growth loop), thereby improving soil leaching efficiency.

Farmers suggested growing Sudan grass on highly saline land, a practice that could be used to promote the development of a local dairy farming industry (Figure 3.9, loop 8, Sudan grass growth loop), which could increase farmer incomes. Some stakeholders opposed the idea of Sudan grass and posed the question of whether it is feasible to convert agricultural land to dairy farming. Both options were included in the model (Figure 3.9, loop 8, Sudan grass growth loop, and loop 6, reclamation loop). In a future study, the comparison of the costs and benefits of these approaches would be useful to analyze in detail.

An area that needs particular attention is the promotion of awareness through technical guidance. Some stakeholders are of the view that if enough resources are made available for an awareness campaign, farmers can be led to adopt technological measures (*e.g.* advanced irrigation methods), which would be helpful in improving crop yields (Figure 3.9, loop 5, ditch construction loop). Other stakeholders highlighted small landholdings as a major hurdle for the adoption of advanced technologies. They also highlighted the need for technical guidance for reclamation techniques, for rainwater harvesting methods, and in receiving government subsidies. The government needs to implement initiatives in capacity building and social awareness as well as measures to transfer more power to stakeholders to achieve an improvement in their societal behaviors and roles. The complete comprehensive qualitative model contains three more thematic models addressing the environmental, governmental influence, and social and industrial aspects of the system, but due to space limitations only the agriculture thematic model was discussed in detail in this paper.

3.5 Discussion

This paper covers the first phase of a long-term study in which the authors are involved; the first phase (described in this paper) involves developing a qualitative system dynamics modeling approach to help initialize the involvement of key stakeholders in both the development and use of a model to address a specific issue in a watershed (in this case soil salinity in the Rechna Doab in Pakistan). Past studies have highlighted the significant increase in salinity in the study area over the last few decades (Khan *et al.* 2008; Qureshi *et al.* 2004; Rehman *et al.* 1997a, b, c, d, e). Recent mega-projects (*e.g.* the "SCARP V" and "Bio Saline project") have also identified soil salinity as the most critical issue in the study area. Nearly all research studies in the area have concluded that the problem of secondary salinization can be solved by adopting good management practices through strong stakeholder participation (for example through the development of a holistic model (Khan *et al.* 2009; Kuper, 1997)), but no initiative has been undertaken to date. The current study is the first of its kind in the project area to involve the active participation of stakeholders. The main purpose of this paper was to describe this relatively simple and cost-effective approach (based on CLDs) to initialize stakeholder participation in the exploration of important water resources issues in agricultural watersheds in developing countries. However, dynamic behavior cannot be inferred from qualitative modeling alone (Richardson, 1996). In the future (*i.e.* in the second phase of this study), the qualitative group CLD model that was developed in this study will be quantified. The purpose of this study was to demonstrate the usefulness of using causal loop diagrams to involve key stakeholders in the initial stages of model development, to facilitate stakeholder discussions, and to develop an integrated perspective on complex issues in agricultural water management.

A frequent comment of stakeholders that participated in the study was that they found the CLD modeling exercise to be very useful for creating awareness and understanding the interaction between different system components. They were very satisfied with the CLD diagrams that they built, and they appreciated the transparency of the process. The participating stakeholders highlighted the need of adapting this approach for increasing social awareness, group learning, and consensus between stakeholders for other problems in their watershed. The modeling framework used in this research is based on a cost and time-effective approach, which makes it more easily adoptable in developing countries. It is also easily understood by non-modeling professionals and provides support for ongoing dialogue processes.

The model developed in this study for soil salinity management is based on an approach with broad boundaries and diverse socio-economic and physical variables, developed with the involvement of stakeholders. It is therefore quite different from the other available physical (e.g. SaltMod, SWAP, DRAINMOD-S, Hydrus) and system dynamics salinity (Giordano *et al.* 2010; Khan and McLucas, 2006; Saysel and Barlas, 2001) models. For example, Saysel and Barlas (2001) used the integration of four physical processes for the dynamic simulation of salt accumulation without consideration of the effects of soil salinity changes on land use, farmer income and industrial growth in the region. In another study, Khan and McLucas (2006) used a real data set for developing reference modes for system dynamics model development. This study was conducted in Australia and only the effect of tree removal on soil salinity changes was investigated. Giordano *et al.* (2010) also developed a soil salinity monitoring system through system dynamics modeling. However, none of the above studies attempted to include stakeholder perspectives and socio-economic issues in the modeling process. For example, components that were included in the model developed as part of this study, such as land use change, government subsidies and stakeholder awareness, have not been investigated in the past in any soil salinity system dynamics model.

There is a strong need for a modeling tool, such as the one developed in this study, that facilitates, through modeling, the understanding of the dynamics of the soil salinity process from both environmental as well as socio-economic perspectives. The stakeholder-built causal loop models built in this study will be the basis for a quantitative system dynamics simulation model in a future second phase of this study. Such a model will be capable of simulating the socio-economic and environmental aspects of soil salinity in an integrated way (along with feedbacks). Due to their integrated nature, system dynamics models are very useful for analyzing the issue of soil salinity at a broader level. Thus, the joint consideration (and dynamic coupling) of more detailed, physically based models and group built system dynamics models will be an important future research topic. Informal and formal coupling approaches are needed to use disciplinary and interdisciplinary knowledge and will be investigated in the second phase of this research.

3.6 Conclusions

This paper proposed a step-wise process for the initialization of stakeholder engagement in agricultural watershed management through qualitative causal loop model building under the constraints of limited time, expertise, and financial resources. This study is the first of its kind aimed at an integrated analysis of the issue of soil salinity on a sub-watershed scale with the active participation of stakeholders through causal loop diagrams. The results of the case study indicate that causal loop diagrams are an effective and simple method to initialize stakeholder involvement in the development of qualitative models aimed at addressing complex issues such as soil salinity management. The merged group CLD model developed in this study covered important aspects from land use changes to socio-economic conditions in Rechna Doab, Pakistan. The causal loop diagram provides an excellent platform for group model building that allows key stakeholders from different organizations and groups to share their views and learn from each other while developing a more thorough and holistic understanding of the particular system that they are exploring.

During the qualitative CLD modeling process in the case study explored in this research project, stakeholders proposed various policies with special reference to economic, social, environmental and technical measures. All stakeholders were in agreement that the soil salinity problem in Rechna Doab is due to an inequitable distribution of surface water supply, which forces farmers to use marginal-quality groundwater to irrigate their crops. Farmer organizations indicated their concern with the government policy of canal lining, and recommended further studies to investigate whether canal lining increased surface water supply or deteriorated groundwater quality through reduced seepage. All stakeholders highlighted the need for an awareness campaign dealing with rainwater harvesting and technological adaptation at the farm level. All stakeholders in the case study were satisfied with the model they had developed, and highlighted the need of adopting this approach for other environmental issues in order to build a better understanding of complex environmental problems, as well as to increase social awareness, group learning, and consensus between stakeholders.

Evaluating the consequences of different stakeholder-recommended polices is a key challenge, which must be tested through a fully quantified system dynamics model (*i.e.* a fully quantified group-built causal loop diagram). This is the next phase of this research project. The future quantified form of the model will be capable of supporting decision-making in soil salinity management, considering stakeholder perceptions as well as social, environmental and economic aspects of the problem.

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Appendix

Appendix 3A

Experts	**Decision Makers**
• International Water Logging and Salinity Research Institute (IWASRI) • Land Reclamation Department • Soil Salinity Research Institute • Research Organizations • Consultants Agriculture Department.	• Water and Power Development Authority (WAPDA) • Punjab Irrigation Department • Ministry of Agriculture and Livestock • Local Governments • Area Water Boards
Implementers	**Users**
• Agriculture Engineering Department • Water Management Department • Water and Power Development Authority (WAPDA) • Environmental Protection Agency • NGO • Area Water Boards	• Agricultural Machinery Industry • Industrial Sector • Farmer Organizations • Local Farmers • Agriculture Businesses • Domestic consumers • Agriculture Businesses • Domestic consumers

Preliminary list of stakeholders with their respective roles

Appendix 3B

1. **Dormant stakeholders**

2. **Discretionary stakeholders**
   Provincial Agriculture Engineering Department
   Punjab Agriculture Department
   Punjab Soil Testing Laboratory
   Directorate of Land Reclamation (Sub department of Punjab Irrigation Department)
   Research Groups (i.e., International Irrigation Management Institute, International Water Logging and Salinity Research Institute)
   Consultants
   Non-Governmental Organization

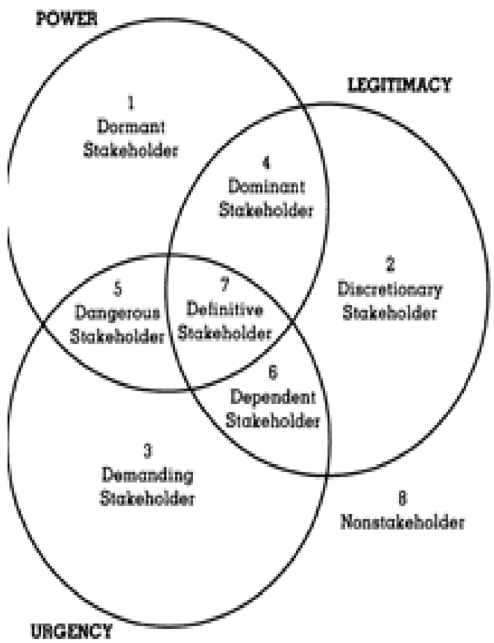
3. **Demanding stakeholder**

4. **Dominant stakeholder**
   Local Government
   Irrigation Department
   Industry

5. **Dangerous stakeholder**

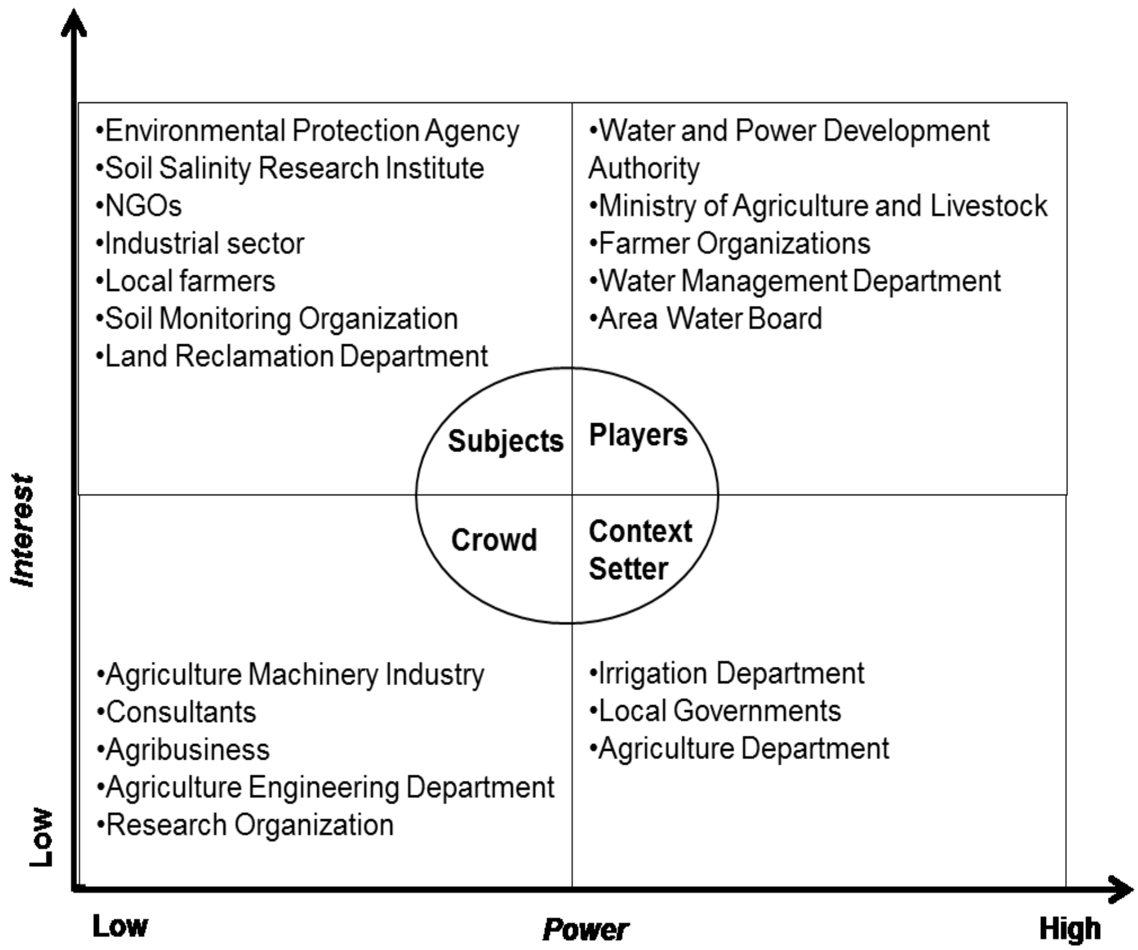
6. **Dependent stakeholder**
   Local farmers
   Agribusiness
   Domestic consumers
   Agricultural machinery industry

7. **Definitive stakeholder**
   Water and Power Development Authority
   Farmer Organizations
   Ministry of Agriculture and Livestock
   Soil Salinity Research Institute
   Water Management Department
   Area Water Board



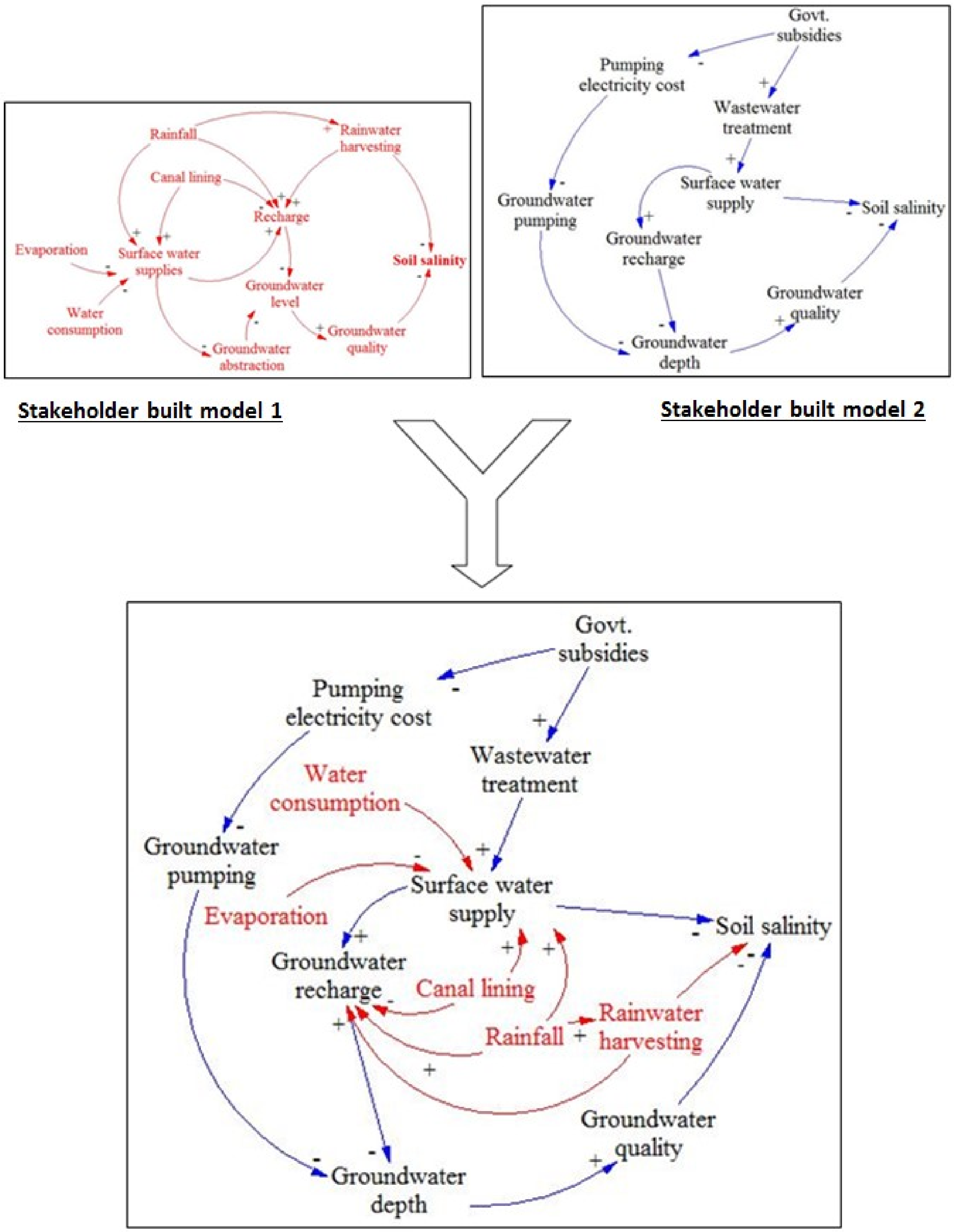
Stakeholder typology with attributes

Appendix 3C



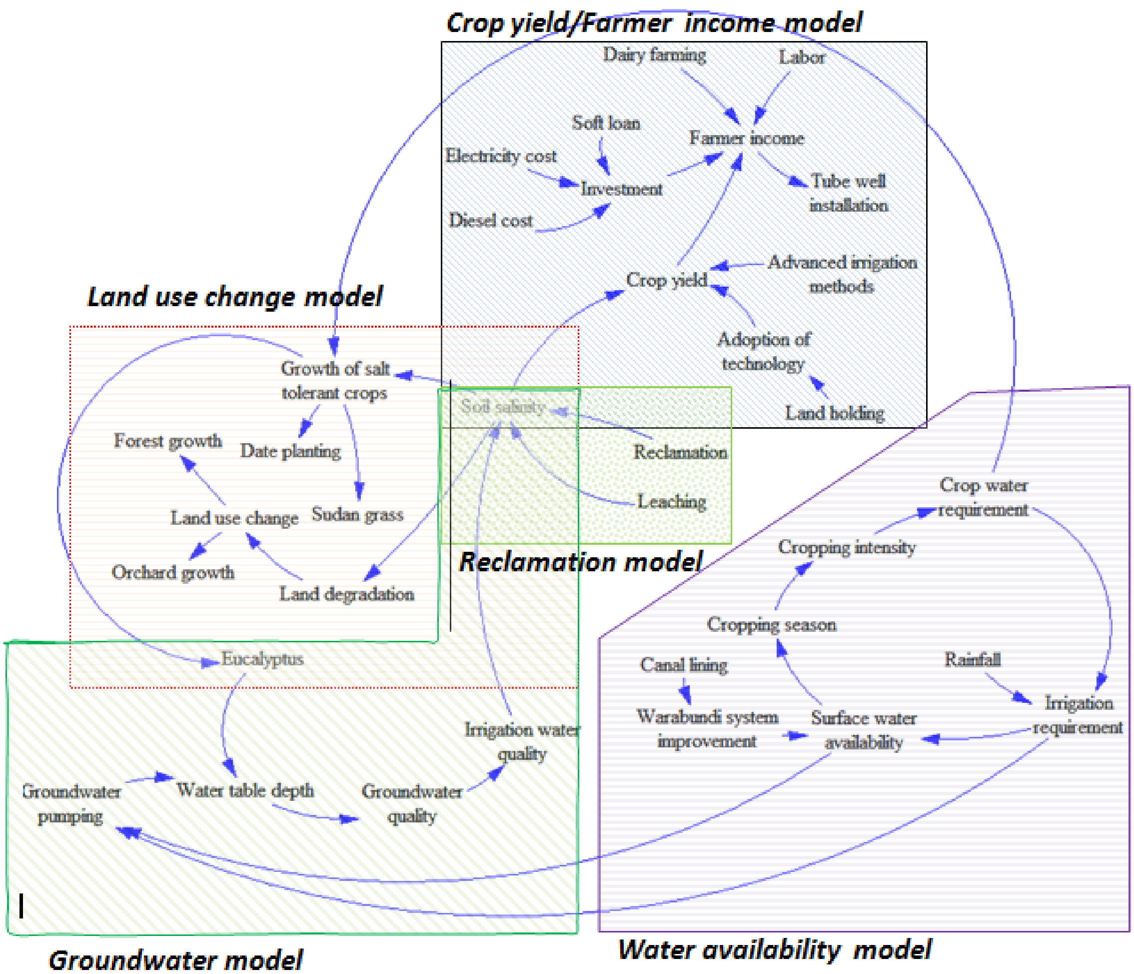
Power *vs.* interest grid of stakeholders

Appendix 3D



Example of the merging procedure for two individual causal loop diagram models

Appendix 3E



Merging of five modeling sub-systems in the agriculture thematic model

CONNECTING TEXT TO CHAPTER 4

The qualitative model, developed in Chapter 3 based on causal loop diagrams, aids in the development of an integrated perspective on complex issues but cannot be used as such to study the dynamic behavior of the system nor to evaluate the consequences of stakeholder recommended policies. In this chapter, the final causal loop diagram, developed in Chapter 3, is classified into physical and socio-economic aspects and the socio-economic and environmental aspects of the model are quantified. Dynamic relationships between different variables are presented through mathematical relationships and a complete model quantification is provided in the form of a stock and flow chart. Furthermore, the results of the structural and behavior validation tests are provided in terms of model testing. All equations of auxiliary, stock, data, lookup, constant, subscripts, range and reality checks are provided at the end of this chapter.

This chapter was published in the Journal of Hydrology (Inam et al. 2017). The format has been modified to be consistent within this thesis. All literature cited in this chapter is referenced at the end of this chapter.

CHAPTER 4: **Coupling of a Distributed Stakeholder-Built System Dynamics Socio-Economic Model with SAHYSMOD for Sustainable Soil Salinity Management. Part 1: Model Development**

Azhar Inam, Jan Adamowski, Shiv Prasher, Johannes Halbe, Julien Malard, Raffaele Albano

Abstract

Effective policies, leading to sustainable management solutions of land and water resources, require a full understanding of interactions between socio-economic and physical processes. However, the complex nature of these interactions, combined with limited stakeholder engagement, hinders the incorporation of socio-economic components into physical models. The present study addresses this challenge by integrating the physical Spatial Agro Hydro Salinity Model (SAHYSMOD) with a participatory group-built system dynamics model (GBSDM) that includes socio-economic factors. A stepwise process to quantify the GBSDM is presented, along with governing equations and model assumptions. Submodules of the GBSDM, describing agricultural, economic, water and farm management factors, are linked together with feedbacks and finally coupled with the physically based SAHYSMOD model through commonly used tools (i.e. MS Excel and python script). The overall integrated model (i.e. GBSDM-SAHYSMOD) can be used to help facilitate the role of stakeholders with limited expertise and resources in model and policy development. Following the development of the integrated model, a testing methodology was used to validate the structure and behavior of the integrated model. Model robustness under different operating conditions was also assessed. The model structure was able to produce anticipated real behaviours under the tested scenarios, and therefore, it can be concluded that the formulated structures generate the right behaviour for the right reasons.

Keywords: System dynamics modeling, SAHYSMOD, Model coupling, Stakeholders, Soil salinity

4.1 Introduction

Physically based modeling tools are widely used for evaluating soil salinity management alternatives. Estimation of soil salinity by conventional physically based modeling techniques (e.g. LEACHM, SALTMOD, DRAINMOD-S, SWAP, HYDRUS) (Hutson and Wagenet, 1989; Kandil *et al.* 1995; Oosterbaan and de Lima, 1989; Van Dam *et al.* 1997) is sometimes problematic due to, among other issues, inaccuracies in predicting local conditions, stakeholder perspectives and socio-economic factors. Physically based models define socio-economic conditions, such as income, benefits, subsidies and GDP growth, exogenously (i.e. they are outside of system boundaries, and stakeholder preferred socio-economic scenarios are not used to test different policies) (Davies, 2008). Exogenous specification of socio-economic conditions narrows model boundaries and results in a limited ability to propose sustainable solutions under specific conditions (Nutt, 2002).

For effective policy formulation and sustainable management of land and water resources, a full understanding of soil salinization processes from a more holistic perspective with improved tools is needed. The methodology proposed in this paper addresses such limitations by explicitly incorporating the strengths of a well-tested physically based agro-hydrological soil salinity model (SAHYSMOD) with a group (i.e. stakeholder) built system dynamics model, representing stakeholder perspectives and socio-economic conditions of the study area. In the first phase of the study published in Inam *et al.* [2015], the development of a participatory system dynamics model (PSDM) was constrained by limited stakeholder expertise, financial resources and time. This situation is common in many developing countries. As such, the approach developed in (Inam *et al.* 2015) was focused on addressing these constraints (i.e. limited expertise, finances, and time). Key stakeholders (Ministry of Food, Agriculture and Livestock, agricultural industries, NGOs, research organizations, Ministry of Water and Power, the Irrigation Department, farmer organizations, and the Land Reclamation Department) were engaged and their views (regarding the causes and consequences of soil salinity, and feedback loops and strategies to address soil salinity) were represented in the form of qualitative casual loop diagrams (CLDs) (see (Inam *et al.* 2015) for details). The stakeholder built CLDs captured the full details of the system through physical, as well as socio-economic, variables. The proposed approach in the current study is a continuation of the first phase, and covers the quantification details of the stakeholder built qualitative CLDs, as well as the coupling details of the quantified group built system dynamics model with the physically based model (SAHYSMOD).

The sections of this paper are structured as follows. The manuscript begins with an introduction of the use of physically based models (P) in soil salinity management and their limitations regarding socio-economic details (section 4.1), followed by a summary of integrated soil salinity models developed to date (section 4.2). A description of the study area is then provided (section 4.3), followed by details of the coupled P-GBSDM model components (section 4.4) along with quantification details of the GBSDM (section 4.4.2). The model coupling procedure is then discussed briefly (section 4.5). A companion paper will describe the coupling of the physically based (P), and group built system dynamics model (GBSDM), in detail and analyze a series of simulation experiments to evaluate the P-GBSDM model performance and applications. Model coupling is followed by model testing and evaluation (section 4.6). Model strength and future work are then described (section 4.7), followed by concluding remarks (section 4.8).

4.2 State of the Art in Integrated Soil Salinity Modeling

A number of integrated soil salinity models exist in the literature that link components of a larger system, evaluate broader consequences, represent structural details, estimate uncertainties and evaluate physical changes in the context of environmental change. However, their main focus is on biophysical aspects rather than socio-economic aspects. Integrated modeling approaches can be classified as compartment modeling and holistic modeling [*Cai et al.* 2003]. A compartment modeling approach (loose coupling) [*Said et al.* 2005; *Markstrom et al.* 2008*; Ragab and Bromley*, 2010; *Barthel et al.* 2012] transfers data exogenously between two models and considers them as separate units, whereas holistic modeling (one unit) [*Kollet and Maxwell,* 2006; *Smerdon et al.* 2007; *Zhang and Werner,* 2009; *Weill et al.* 2011; *Brunner and Simmons,* 2012] endogenously exchanges data between different components by embedding both models into a single unit. The current study combines the strength of both approaches by using a holistic modeling approach for the GBSDM, and a compartment modeling approach to link the GBSDM with the physically based model (SAHYSMOD). The scope of this study was very large and only integrated modeling studies of soil salinity are discussed in this section.

Ragab [2002] focused on evaluating the distribution of soil salinity in Egypt by taking into account the effects of irrigation systems, soil type and irrigation water quality. In this study, a comprehensive modeling tool named SALTMED was developed by linking single process-oriented models of infiltration, evaporation, plant water uptake and water and solute transport, but did not include a socio-economic component. Similarly, in another study by *Laudien et al.* [2008], four existing models of groundwater, irrigation water demand, domestic water demand and soil salinity were coupled with ArcGIS Engine to evaluate the impacts of water exploitation on changes in groundwater and soil salinity. These integrated modeling studies used scripted languages to exchange output between models without any feedback between system components, and thus, did not really simulate the dynamic system behavior.

Some studies attempted to overcome the limitations of dynamic simulation by translating physically based models into system dynamics modeling (SDM) environments. For example, *Saysel and Barlas* [2001] used the integration of four physical processes of root zone salinization (i.e. irrigation, drainage, groundwater discharge and groundwater intrusion) for the dynamic simulation of salt accumulation using system dynamics modeling. Sub-models were linked with feedbacks, using a solid set approach. Another study used a real data set to develop reference modes for SDM development [*Khan and McLucas,* 2006]. This work was conducted in Australia and used narrow model boundaries focusing on one aspect: the effect of tree removal on soil salinity. *Giordano et al.* [2010] also developed a soil salinity monitoring system through SDM. Similarly, *Nozari and Liaghat* [2014] developed an SDM with a focus on estimating drainage water quality and quantity and subsequent effects of drainage effluent on soil salinity. Their model was based on water balance, salt balance and a convention-dispersion equation. None of the above SDM studies attempted to include stakeholder perspectives or socio-economic issues in the soil salinity modeling process. *Prodanovic and Simonovic* [2007] addressed the issue of incorporating socio-economic issues by coupling hydrological and socio-economic models for a climate change impact assessment of the Upper Thames River Basin, Canada. They used a solid set approach by translating both models into Java language. This type of coupling approach somewhat limits the model applicability for local stakeholders since its modification requires significant expertise in Java programming. In addition, this approach was developed without engaging stakeholders in the modeling process.

The coupled model developed in this study provides a flexible modeling platform using the SDM environment. One of the main strengths of this SDM approach is that it is flexible and allows for the inclusion of different types of variables. It provides a unique contribution to the modeling literature by providing an approach to facilitate the integration of a well-developed 'expert' soil salinity physically based model (SAHYSMOD) and a group-built socio-economic system dynamics model. Broad system boundaries, diverse socio-economic and physical variables, and stakeholder engagement in model development make this study unique and very different from the other available physically based (e.g. SALTMOD, SWAP, DRAINMOD-S, HYDRUS, LEACHM) and system dynamics salinity models [*Saysel and Barlas,* 2001; *Khan and McLucas,* 2006; *Giordano et al.* 2010; *Nozari and Liaghat,* 2014]. The modeling framework of the proposed modeling approach used commonly available software tools (i.e. Vensim, MS Excel and Python) that increase its transparency and also make it easy to adopt, even in developing countries. This software provides the flexibility, interactivity and extensibility needed to serve as the "glue" to tie together modules and components and overcome the limitations of a solid set approach to rapidly create a tailored and context-specific application. The proposed approach can be easily understood by non-modeling professionals and other benefits include an increase in social awareness and transparency and improvements in stakeholder participation in decision-making, thus increasing the understanding of stakeholders in managing uncertainties and quantifying losses through soil salinity changes. The modeling framework developed in this research should help to contribute to the understanding of what is important and what stakeholders need to focus on for the future sustainability of their crop-soil-water systems. To the best of the authors' knowledge, no integrated and participatory social-hydrological model of this kind has been developed anywhere in the world.

4.3 Study Area

The coupled physical and group-built system dynamics model (P-GBSDM) was applied on a sub watershed located in the Rechna Doab, Pakistan. The study area lies between 30° 32' N and 31° 08' N latitude and 72° 14' E and 71° 49' E longitude, and covers about 732.50 km^2. It is located in the Rechna 'Doab' basin just above the confluence of the Ravi and Chenab Rivers and lies within the Haveli Canal command area. Potentially cultivatable land, presently unexploited due to high soil salinity levels, makes up 30% of the area. Groundwater depth varies from 3-6 m, with groundwater electrolyte concentrations exceeding 1500 ppm in the middle portion of the basin [*IWSRI,* 2005]. The details of the study area, along with collected data and data analysis, are provided in *Inam et al.* [2017a].

4.4 Coupled Model Description: P-GBSDM

P-GBSDM is an integrated tool that dynamically and explicitly models the nonlinear feedbacks between physical (via the physically based model, P) and socio-economic (via the group-built system dynamics model, GBSDM) systems. P-GBSDM was developed by coupling the Spatial Agro Hydro Salinity Model (SAHYSMOD) [*Oosterbaan,* 1995] with a stakeholder built system dynamics model. Its first component, SAHYSMOD, is a well-developed spatially distributed watershed-scale soil salinity model, which has been successfully applied and tested under arid climatic conditions in various regions of the world [*Kaledhonkar and Keshari,* 2007; *Akram et al.* 2009; *Desta,* 2009; *Liaghat and Mashal,* 2010; *Singh and Panda,* 2012a]. Before coupling it with GBSDM in the current study, it was tested by the authors through model calibration and validation over the study area (see *Inam et al.* [2017a] for details). SAHYSMOD can simulate the long-term effects of management on groundwater level and soil salinity. The second component, GBSDM, is a flexible system dynamics model that allows for the incorporation of socio-economic variables into a physical model, and was formulated through quantification of stakeholder-built qualitative system dynamics models developed in the first phase of the modeling study [*Inam et al.* 2015]. P-GBSDM combines the strength of both modeling platforms and provides a unique modeling tool that is capable of spatially and temporally evaluating changes in soil salinity under different policy scenarios. Thus, it provides a decision support system for evaluating, in a participatory manner with stakeholders, different strategies and policies and answering “What if?” questions.

Socio-economic and environmental processes, such as farm income, government subsidies, land-use changes, crop yield, etc., were modeled with the system dynamics model (GBSDM), whereas the physical processes of water and salt movement in the crop root zone were simulated using SAHYSMOD (i.e. P). The P-GBSDM model is deterministic, with the time unit of simulation being a season (6 months) and the time zone of simulation from 1990 to 2010 (20 years/40 seasons). This greater time unit selection was based on two important considerations: firstly, soil salinization is a slow process and usually takes three to four seasons to appear at the soil surface, and secondly, model simulation with the exchange of input and output variables on spatial scales with smaller time-steps requires significant memory and data availability.

The developed model is capable of simulating a range of management options or answering “What if?” questions under existing bioenvironmental conditions. In the P-GBSDM model, the options include, for example: evaluating canal lining policies for seepage loss reduction, rainwater harvesting, irrigation efficiency improvement, conjunctive surface and groundwater use, optimum cropping practices under saline conditions, and allocating government subsidies to lower electricity rates and incentivize tubewell installation to improve vertical drainage in the area. These management options were based on stakeholder-proposed strategy options and some of them are evaluated in a subsequent companion paper. The following section briefly describes the components of the integrated model.

4.4.1 SAHYSMOD Component of the Integrated Model (P)

SAHYSMOD combines the agro hydro salinity model, SALTMOD, with the polygonal groundwater model, SGMP (Standard Groundwater Model Package), to simulate long-term effects of management practices on soil salinity changes in root zones, as well as in aquifers. SAHYSMOD was selected from among many available soil salinity physically based models for several reasons:

1. It provides a wide range of flexibility in terms of agricultural practices (e.g. farmer response to soil salinity), and options of horizontal – as well as vertical – drainage, surface drainage, conjunctive water use, and crop rotation with change in the soil salinity profile.
2. It addresses the majority of management measures (e.g. vertical drainage) identified in the first phase of the modeling study [*Inam et al.* 2015].
3. It is able to evaluate the strategies of canal lining and tubewell abstraction for aquifer sustainability. This helps in evaluating the effect of exponential tubewell growth in the area [*Qureshi et al.* 2003] and assessing impacts of the on farm water management policy of lining.
4. Soil salinity usually appears in patches; a spatially distributed model is helpful for recommending space-based solutions with consideration of all factors, such as low water availability due to farm location on the canal network.

SAHYSMOD employs seasonal time-steps, uses seasonal input data and provides seasonal outputs. The number of seasons per year can vary from one (twelve-month duration) to four (three-month durations). Seasonal salt and water balance were used as inputs and were related to surface water hydrology (e.g. rainfall, potential evapotranspiration, irrigation and runoff) and groundwater hydrology (e.g. groundwater pumping, capillary rise and drainage). Based on common cropping practices on site, a year was divided into two seasons with equal six-month durations (i.e. Rabi (winter) from November to March and Kharif (summer) from April to October). Spatial variation in soil salinity was modeled with a series of 279 square polygons (215 internal and 64 external), each 21 × 21 cm in size with a scale of 1:10000 (Figure 4.1). Each node was considered a separate unit and data, such as soil hydrological parameters, seasonal surface and groundwater hydrology and initial soil salinity, were inputs for each polygon. Nodal network relations were specified for modeling the neighborhood effect. The centroid of each node was representative of the whole polygonal area, and recharge and discharge activities were considered to be occurring at polygon centroids. The nodal network configuration of SAHYSMOD is shown in Figure 4.1.

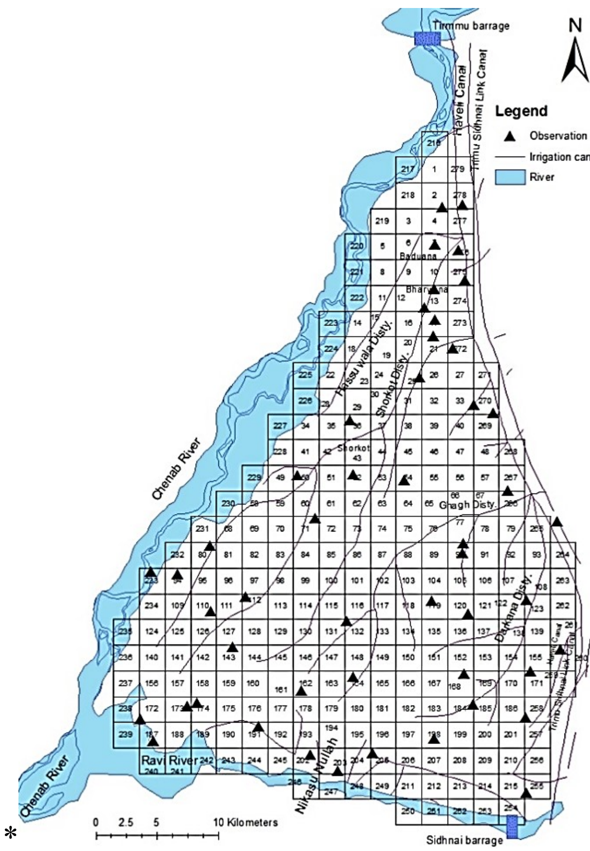


Figure 4.1. Nodal network configuration of SAHYSMOD model

The water and salt balance modules of SAHYSMOD are based on the conservation of mass principle. The model uses Darcy's law and Dupuit's assumptions to describe the two-dimensional movement of groundwater through porous media. SAHYSMOD uses a finite difference method for solving partial differential equations. The whole area is divided into spaces, and the formed subareas are called polygons. The theoretical details about water and salt movement in SAHYSMOD are provided in *Inam et al.* [2017a].

4.4.2 GBSDM Component of the Integrated Model

The socio-economic component of the integrated model (GBSDM) was based on a quantification of stakeholder-built qualitative models developed in the first phase of the modeling study describe in [*Inam et al.* 2015]. GBSDM uses a well-established modeling methodology (system dynamics) which among other available mathematical and numerical methods, is the most appropriate modeling tool for expressing relationships between physical, socio-economic and environmental factors [*Dyson and Chang,* 2005; *Prodanovic and Simonovic,* 2007; *Halbe and Adamowski,* 2011; *Herrero et al.* 2014]. According to *Beall and Ford* [2010], "when faced with complex, multi-stakeholder environmental issues, system dynamics has the greatest potential when used in a participatory fashion by scientists and managers working together with others who also have a stake in land management decisions". Such observations by past researchers – as well as unique modeling features, such as delays, feedbacks, flexibility and transparency [*Sterman,* 2000] – make system dynamics a good candidate for the current modeling study. A widely-accepted system dynamics modeling simulation package, Vensim DSS (Ventana Systems Inc.), was used in this study.

A "downward approach" [*Sivapalan et al.* 2003] was followed to quantify the thematic models extracted from the stakeholder-built CLDs [*Inam et al.* 2015] to develop the system dynamics model (GBSDM). Under this approach, key processes, or first order controls, were identified on thematic maps and then expanded in a stepwise fashion to explore system behavior in full detail. The important steps of model development are as follows:

1. Stakeholder-identified sectors were used as major system attributes. In this study, they were classified into agriculture (Section 4.4.2.1), economics (Section 4.4.2.2), water (Section 4.4.2.3) and management (Section 4.4.2.4) option groups.
2. For each of the identified groups, system dynamics modules were developed and tested through structure and behavior validity tests (Section 4.6).
3. Different SDM modules of each sector were linked together through feedbacks (Section 4.4.3).

4. The system dynamics model from step 3 (GBSDM) was linked with the physical model (P) (SAHYSMOD) through a component modeling technique. Testing of the integrated P-GBSDM was carried out with results of a past implemented policy.

Time-steps and spatial resolution scales of the physical model (P) were followed in GBSDM development in order to achieve temporal and spatial consistency. The complete model consists of various stocks (irrigation efficiency, lined length, constructed capacity, silted capacity, water requirement, farm income, debits and tubewell numbers), a number of rates (seepage, runoff, income, expenditure, decay, construction and water consumption), and lookup or table functions (lining, water harvesting and irrigation efficiency policies, inflation factor, perception states, canal water distribution) that holistically represent the system. Major system components with their feedbacks are shown in Figure 4.12.

The system dynamics modules (GBSDM) can be categorized into four main sectors: agriculture, economics, water and management. Only the equations and controls of the unique components (e.g. empirical equations of canal losses, canal water distribution and allocation, tubewell growth function, increase in tubewell operating cost with depth, government subsidies function, etc., each of which was developed in different past project consulting reports in the study area) of the GBSDM model are discussed here. For well-known equations (e.g. conjunctive water use, water demand, effective rainfall, salt and water stress etc.), references are given instead of providing the equations and details (due to space limitations). More specifically:

1. The *agriculture module* includes agronomic (cropped area, intensity and duration) and water requirement (water demand, conjunctive use and leaching requirement) estimations. Model quantification equations except the unique modeling components were mostly taken from the published literature [*Richards,* 1954; *Ayers and Westcot,* 1985; *Allen et al.* 2005].
2. The *economics module* is based on a relatively simple representation of commonly used macro-economic systems used in agricultural economics. Outputs such as loans, income and expenditure were verified with data acquired from the Statistical Bureau of Pakistan.
3. The *water module* includes irrigation application, groundwater abstractions and a surface water storage sub-model. Water module equations were derived from reports of past projects conducted in the study area [*Qureshi et al.* 2003; *Chughtai and Mahmood,* 2012]. Values of constants, lookup or table functions and equation coefficients were selected from the

literature, stakeholder interviews, discussions with experts and local knowledge of the system. [*Khan et al.* 2003; *Agarwal,* 2012; *Shaikh et al.* 2015]

4. The *management module* includes formulation of management options recommended by stakeholders during the first phase of the study [*Inam et al.* 2015]. Various levels, controls and financial and environmental constraints were created. Values of design parameters, stakeholder perceptions and lookup or table functions were decided through stakeholder interviews. The following sections discuss each of the four individual modules in detail.

4.4.2.1 Agriculture Module

The agriculture module estimates crop water requirements and leaching fraction. It also describes controls of policy variables such as conjunctive water use, land use changes, allocating water for leaching requirement, and crop pattern change. The crop water requirements submodule structure is shown in Figure 4.2.

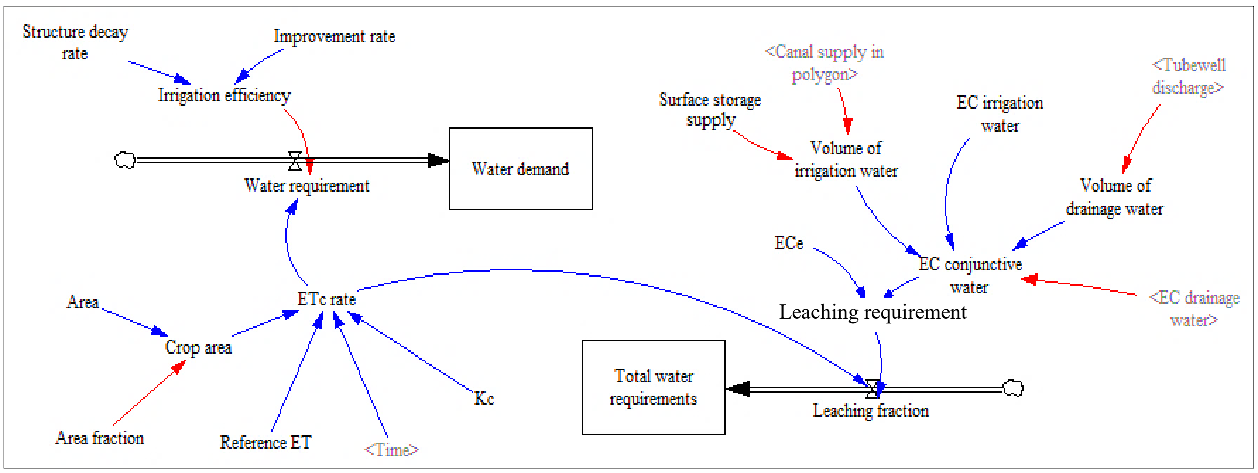


Figure 4.2. Crop evapotranspiration and leaching fraction estimation model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

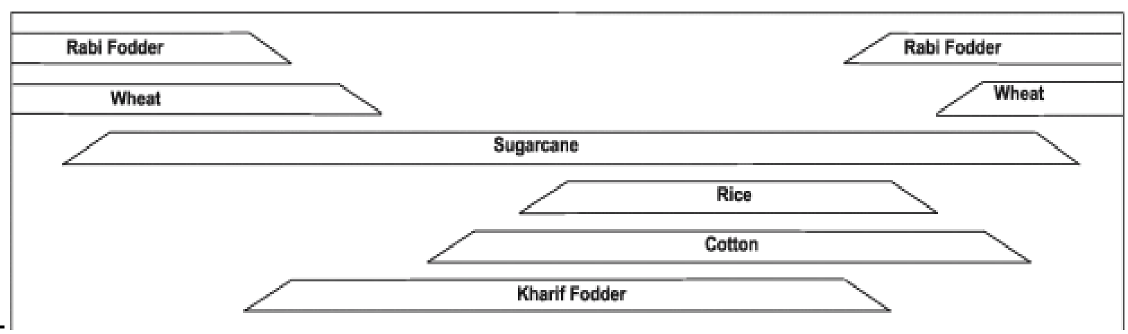
Cropped Area Fraction and Cropping Pattern

Crop cultivated area and cropping pattern as per change in salinity level was calculated through SAHYSMOD (P component). More area was cultivated as the salt balance is reduced below crop tolerance level. Crop tolerance levels were adopted from the well-documented source of the Food and Agricultural Organization of the United Nations (FAO) [*Allen et al.* 2005], whereas soil classification was defined according to USDA criteria [*Richards,* 1954]. High saline zones were regarded as uncultivated areas. The cropping pattern in the non-saline zone was defined as being between the summer (cotton, rice, sugarcane) and winter seasons (wheat, fodder). For this purpose, a seasonal switch through the MODULO function of Vensim DSS was created. This function keeps track of the month of the year and assigns winter and summer crops accordingly.

Culturable command area (CCA) was classified as non-saline, slightly saline, moderately saline and strongly saline. This classification was based on USDA criteria [EC < 4 dS m^{-1} (non-saline), EC = 4-8 dS m^{-1} (slightly saline), EC = 8-16 dS m^{-1} (moderately saline), EC > 16 dS m^{-1} (strongly saline)] [*Richards,* 1954]. Crops were considered to be grown only in non-saline zones, whereas grass and forest grow in slightly saline and moderately saline zones, respectively.

Crop Water Requirements (ET_c)

A commonly used crop water requirement equation ('K_c ET_o' approach) described in FAO Irrigation and Drainage Paper No. 56 [*Allen et al.* 2005] was used for estimating crop evapotranspiration under standard conditions (ET_c). Potential evapotranspiration (ET_o) was calculated from climatic data using the well-known Penman-Monteith equation. Crop coefficient (K_c) values as suggested by *Kaleemullah et al.* [2001] were used (see Figure 4.3). These K_c values were based on a comprehensive literature review and assessment of cropping period in the area.



	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Wheat	1.08	1.15	0.88	0.40							0.35	0.60
Cotton					0.35	0.78	1.12	1.02	0.68	0.45	0.35	
Rice						0.39	1.15	1.38	0.92	0.42		
Sugarcane		0.36	0.61	1.01	1.14	1.18	1.25	1.17	1.07	1.02	0.85	0.47

Figure 4.3. Cropping calendar and Kc values used in the study [*Kaleemullah, et al.* 2001]

Seasonal volume of $(ET_c)_{i.p}$ in m^3 $season^{-1}$ for *ith* crop in *p* polygon was calculated by multiplying potential evapotranspiration (m $season^{-1}$), crop coefficient and cropped area (m^2).

Net Water Requirements

Agricultural water requirements of crops were calculated by dividing crop water requirements by irrigation efficiency, as shown in Equation (4.1):

$$Water\ \ requirement = (WQ)_p = \frac{\left(\sum_{i=1}^{I}((ET_c)_p)_i\right)}{(IrrE)_p} \tag{4.1}$$

Where i is the number of crops per season (I=2), and WQ_p and $IrrE_p$ are crop water requirements (m^3 $season^{-1}$) and irrigation efficiency (dimensionless), respectively, of polygon *p*. For a detailed description of calculating irrigation efficiency per polygon, see Section 4.4.2.4.

Total Water Requirements

Total water requirement is the sum of water requirement and leaching demand, where leaching demand is the amount of water, in addition to crop water requirement, needed to leach excessive salts from the crop root zone. Total water requirements, together with leaching requirements, were estimated through the following equation developed by the FAO [*Ayers and Westcot*, 1985]:

$$(TWQ)_{i,p} = \frac{(WQ)_{i,p}}{1-(LR)_{i,p}} \tag{4.2}$$

Where $TWQ_{i,p}$ and $LR_{i,p}$ are, respectively, total water requirement (m^3 $season^{-1}$) and leaching fraction (dimensionless) for crop i in polygon *p.* Leaching requirement of the study area was assessed by using a standard leaching requirement equation, (4.3), developed by the FAO [*Ayers and Westcot, 1985*]:

$$(LR)_{i,p} = \frac{(EC_{iw})_p}{[5\times(EC_e)_i-(EC_{iw})_p]} \tag{4.3}$$

Where EC_{iw} and EC_e are, respectively, electrical conductivity of irrigation water (dS m^{-1}) and soil root zone (dS m^{-1}) for polygon *p* and crop *i*. EC_e was estimated directly from the output of SAHYSMOD (P component).

Conjunctive Water Use

One potential cause of secondary salinization is the application of marginal quality irrigation water, which can be managed by identifying appropriate strategies (discussed in *Inam et* *al.* [2017c]) for managing surface and groundwater resources. Irrigation water quality is highly dependent on the proportion and quality of surface and groundwater in irrigation water. Volumes of different mixes were controlled in Vensim DSS, whereas, changes in groundwater quality were simulated with SAHYSMOD (P component). Irrigation water quality EC_{iw} was assessed by a well-known conjunctive water use equation reported in FAO Irrigation and Drainage Paper No. 29 [*Ayers and Westcot,* 1985].

4.4.2.2 Farm Economics Module

Farm income depends directly on crop yield, which is strongly affected by soil salinity and water stress. The farm economics module was linked through feedback loops to the agriculture and management option modules. The crop water requirements and irrigation water quality estimated in the agriculture module (section 4.4.2.1) were used to estimate soil salinity and water stress. In the next step, farm income generated from the net crop yield controls the selection of appropriate farm management techniques available in the management option module (section 4.4.2.4). Figure 4.4 shows the structural details of the crop yield and income sub-model.

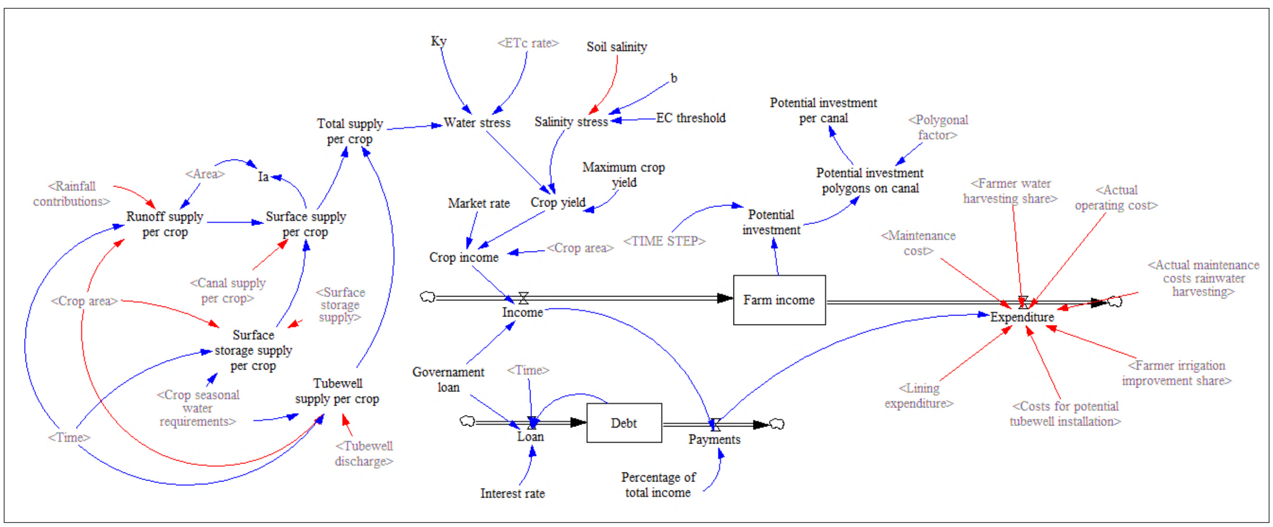


Figure 4.4. Crop yield and income sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

Crop Yield

Yield functions were developed in GBSDM to assess the effect of water and salinity stress on crop yield. To calculate the actual average yield, maximum crop yield data of the study area (i.e. yield under no stress conditions) as reported by the Statistics Department of Pakistan was adjusted through salinity-yield stress and water-yield stress relationships reported in FAO

Irrigation and Drainage Paper No. 56 [*Allen et al.* 2005]. The crop yield function was estimated as follows:

$$(Y_a)_{ip}[f(W_i, S_i)] = \ (Y_m)_i \times \ (\beta_w)_{ip} \ \times (\beta_s)_{ip} \qquad (4.4)$$

Where $(Y_a)_{ip}$ is the actual yield of crop i in p polygon (kg season^{-1} m^{-2}), which is a function of salinity and water stress for crop i in p polygon; Y_{mi} is the maximum expected yield when a crop is under no salt or water stress (kg season^{-1} m^{-2}); β_w and β_s are the percentage reductions in maximum crop yield due to water and salinity stress (dimensionless), respectively. β_w and β_s were estimated from FAO developed relationships [*Allen et al.* 2005]. Values of b, $EC_{threshold}$ and K_y for selected crops (Table 4.1) were taken from FAO Irrigation and Drainage Paper No. 56 [*Allen et al.* 2005].

Table 4.1. Crop yield stress estimation parameters [*Allen et al.* 2005]

Crops	***Ky***	***b* (% (dS m^{-1})$^{-1}$)**	***EC$_{threshold}$* (dS m^{-1})**
Wheat	1.05	7.1	6.0
Cotton	0.85	5.2	7.7
Rice	1.0	12.0	3.0
Sugarcane	1.2	5.9	1.7
Kharif fodder	1.0	5.7	1.5
Rabi fodder	1.0	4.3	2.8

Income and Expenditure

Net income per polygon was calculated in terms of seasonal gross margin, estimated through the difference in farm expenditures and revenue. Farm gross margin ($ season^{-1}) is defined in Equation (4.5):

$$(GM)_p = (Rev)_p - (Exp)_p \qquad (4.5)$$

Where GM_p is gross margin per polygon, Rev_p is total revenue ($ season^{-1}) and Exp_p is total expenditure ($ season^{-1}) of polygon p. Revenue was considered to be the sum of farm income and government loans:

$$(Rev)_p = \ \sum_{i=1}^{I} \left(P_i \times (Y_a)_{\ i,p} \times (A_c)_{i,p}\right) + TL_p \qquad (4.6)$$

Where P_i is the market price of crop i (\$ kg^{-1}) (values were taken from published reports of the Statistics Department of Pakistan), $(Y_a)_{i,p}$ was estimated from Equation (4.4) and $(A_c)_{i,p}$ was calculated through SAHYSMOD (P component).

The government loan module was based on the assumption that farmers ask for government loans when income is less than expenditures. This assumption was based on feedback from farmer interviews conducted during the first stage of the study [*Inam et al.* 2015]. The model limits the availability of loans when the total debt becomes greater than the farm annual income. The annual loan was considered to be the sum of the loan amount and the compound interest of the debt stock (as shown in Figure 4.4):

$$TL_p = IR * Debt_p + L_p \tag{4.7}$$

Where TL_p is the total loan (\$ year-^{1}) for polygon p, IR is the interest rate (dimensionless) taken from reports of the Statistical Bureau of Pakistan, $Debt_p$ is total debt (\$) taken as the difference between total loan and payments, and L_p is the annual loan for polygon p. Farm expenditure (\$ season^{-1}) is defined in Equation (4.8):

$$(Exp)_p = \sum \left(\sum_{m=1}^{M} CP + \sum_{n=1}^{N} VC \right)_p + LP_p \tag{4.8}$$

Where CP is the capital cost (\$ season^{-1}) or investment in management techniques described in the management option module (Section 4.4.2.4), and M is the number of capital cost factors. Capital cost is a one-time investment and was considered only once in the model. VC indicates variable cost of n crop (\$ season^{-1}). The main variable cost factors considered in the study were operation and maintenance of management techniques described in the management option module, and the unit area cost of farm inputs. Unit area costs of farm inputs and irrigation water were taken from reports of the Statistical Bureau of Pakistan. LP_p represents loan payment amounts (\$ year^{-1}) for polygon p. Based on feedback from local stakeholders, it was assumed that a farmer uses 2% of their annual earnings for paying back their loan.

4.4.2.3 Farm Water Module

The farm water module describes water availability and distribution from different resources (e.g. rainfall, canal supplies and groundwater extraction).

Effective Rainfall

In irrigated areas, rain is considered the main source of water, and canal water requirements are estimated through the difference between effective rainfall and crop water demand. Effective rainfall is the fraction of total rainfall that is stored in the crop root zone and effectively utilized by the plant. Effective rainfall depends on soil texture and structure, land use and cover, climate, topography and depth of root zone. Figure 4.5 shows structural details of the effective rainfall sub-model. Effective rainfall contribution was estimated by using the relationship developed by *Brouwer and Heibloem* [1986] and is shown in Equations (4.9) and (4.10) for high and low rainfall events, respectively.

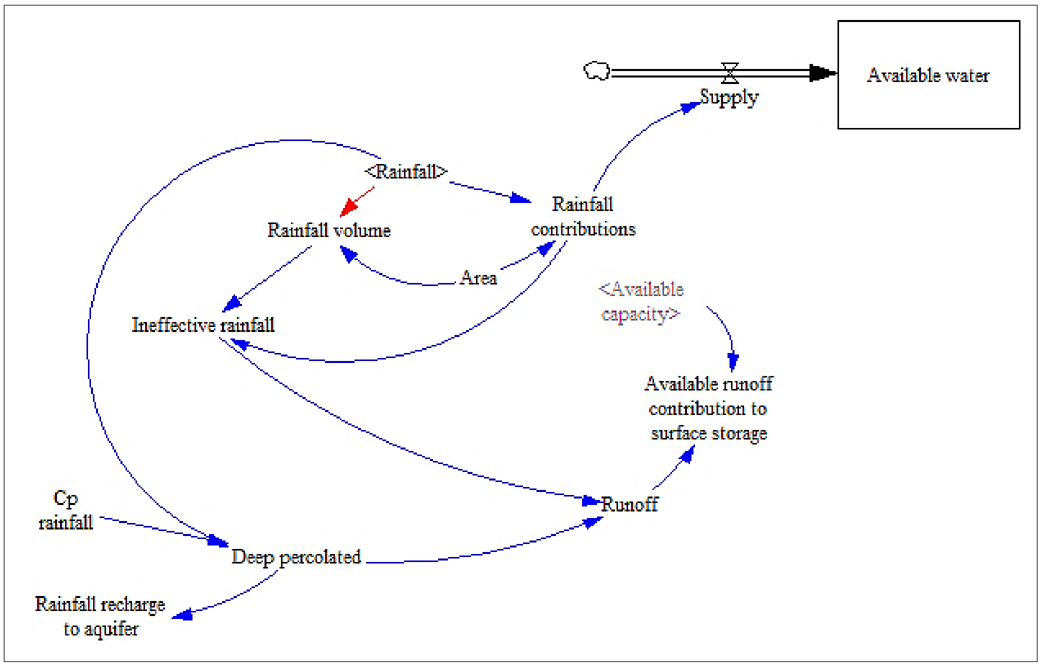


Figure 4.5. Effective rainfall sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

$$(RC)_p = \sum_{n=1}^{N} \big(0.8 \ \times (R - 25)\big) \times A_p \qquad \text{if PP} > 75 \ mm/mont \tag{4.9}$$

$$(RC)_p = \sum_{n=1}^{N} \big(0.6 \ \times (R - 10)\big) \times A_p \qquad \text{if PP} < 75 \ mm/mont \tag{4.10}$$

Where RC_p is rainfall contribution (m^3 season^{-1}) for polygon p and R is rainfall or precipitation (mm month^{-1}). N is the number of rainfall events in a season. Effective rainfall amount was computed on a monthly basis and then summed seasonally to give seasonal effective rainfall. A_p is the area of polygon p (m^2). Model grid cell size in SAHYSMOD is fixed at 2100 m × 2100 m and therefore A_p is taken as 441×10^4 m^2.

In order to estimate the rainfall contributions in deep percolation and runoff, ineffective rainfall was further partitioned between deep percolation and runoff losses. Deep percolation is important for aquifer recharge. Only 20% [*Khan et al.* 2003] of total rainfall was considered to be deep percolation and this was used as an input in SAHYSMOD, whereas, 40% of runoff (i.e. the difference between ineffective rainfall and deep percolation losses) was considered a runoff contribution to surface storage in order to account for the interception and depression storage losses.

Irrigation Distribution and Application

Canal water is used to supplement irrigation supplies when effective rainfall is not sufficient to meet crop water needs. Water distribution over the entire command area of the canal is highly uneven and head end reaches of the canal commonly receive more water than tail end reaches [*Bandaragoda,* 1996]. In the first phase of this study [*Inam et al.* 2015], stakeholders (i.e. farmers, NGOs, consultants, etc.) highlighted this aspect and showed interest in equitable water distribution for sustainable solutions. Equitable and inequitable distribution was achieved through a distribution switch. It can be turned on and off by setting the value to 0 or 1, where 0 means equitable distribution and 1 means inequitable distribution. Figure 4.6 shows the structure of the irrigation distribution sub-model.

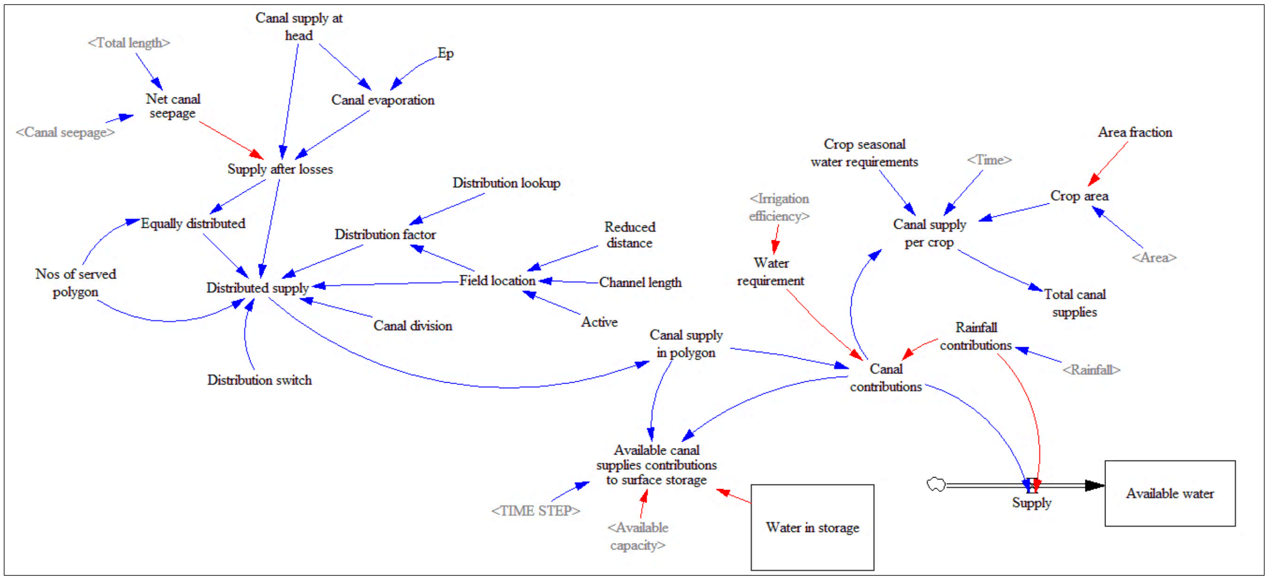


Figure 4.6. Irrigation distribution and application sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

Flow data (1990-2010) at the canal head and canal command area (CCA) of the irrigation network was collected from the Punjab Irrigation Department, Pakistan; effective canal supplies were calculated by subtracting evaporation and seepage losses. It is assumed that 8% of the total canal supply is lost through evaporation, in line with the findings of *Arshad* [2004] in the same study area. Upstream and downstream areas of the CCA are partitioned on a 50:50 basis. Reduced distances of polygons over canal lengths were specified for each canal by overlaying canal layouts and polygonal maps in ArcGIS. Equation (4.11) summarizes the decision process of polygon categorization as upstream and downstream:

$$FL_{p,c} = \frac{RD_p}{CL_c} \begin{cases} \leq 0.5 & Upstream \\ > 0.5 & Downstream \end{cases} \tag{4.11}$$

Where $FL_{p,c}$ is the polygon p location on a particular canal c, and the location of each polygon (p) along a canal (c) is estimated with the ratio of reduced distance (RD) (m) and canal length (CL) (m). If the computed ratio was less than or equal to 0.5, the polygon was considered to be on the upstream side, and vice versa. The distribution factor of water along the canals was defined through a lookup or table function. It provides flexibility for water distribution over the canal length, including the option of inequitable distribution between upstream and downstream farmers. The distribution factor is a policy option and can be modified for conducting different simulation experiments.

Canal irrigation contributions were established with a demand-based approach. In the first step, crop water requirements are met through rainfall, and in the case of a deficiency, water was supplied from the canal irrigation system for polygon *p*. The decision control system of irrigation supplies from the canal system can be summarized in Equations 4.12 and 4.13 as follows:

$$(ET_c)_p = \sum_{i=1}^{I} (ET_c)_{i,p} \tag{4.12}$$

$$CS_p = \begin{cases} (ET_c)_p - (RC)_p & (ET_c)_{i,p} > (RC \\ 0 & (ET_c)_{i,p} < (\end{cases} \tag{4.13}$$

Where $(ETc)_p$ is crop water requirement for polygon p (m^3 $season^{-1}$), calculated by summing the crop water requirements of crop i grown in polygon p, and CS_p is the canal supply in polygon p (m^3 $season^{-1}$). After meeting the crop water requirements, the excess supply in a canal irrigation system was deemed an excess canal supply contribution to surface storage (C_p) in Equation (4.28).

Finally, irrigation water supply per polygon is distributed between crops using a weighted function based on cropped area and water requirements of individual crops. The function is summarized in Equation 4.14:

$$(CS)_{i,p} = \frac{CS_p}{A_p} \times A_{p,i_a} \times \left(\frac{A_{p,i_a} \times (ET_c)_{i_a}}{\left(A_{p,i_a} \times (ET_c)_{i_a}\right) + \left(A_{p,i_b} \times (ET_c)_{i_b}\right)} \right) \tag{4.14}$$

Where $CS_{i,p}$ is the canal supply for crop i in polygon p (m^3 $season^{-1}$), A_{p,i_a} is the cropped area of crop variety "*a*" in polygon p (m^2) (inputted directly from SAHYSMOD (P component) by taking farming responses and soil salinity tolerance levels into account), and $(ET_c)_{i_a}$ is the crop water requirement of crop variety "*a*" (mm $season^{-1}$). Values of water requirements for different varieties were extracted from the FAO Irrigation and Drainage Paper No. 56 [*Allen et al.* 2005].

Groundwater Abstraction

Groundwater pumping was used to supplement irrigation supplies when effective rainfall and canal supplies were not sufficient to meet crop water needs; additional benefits include vertical drainage of waterlogged areas. In some cases, excessive groundwater pumping also affects groundwater quality by removing fresh zone layers in an aquifer. Hence, evaluation of groundwater management measures becomes important in judging aquifer sustainability in the long term. Figure 4.7 shows the structure of the groundwater abstraction sub-model.

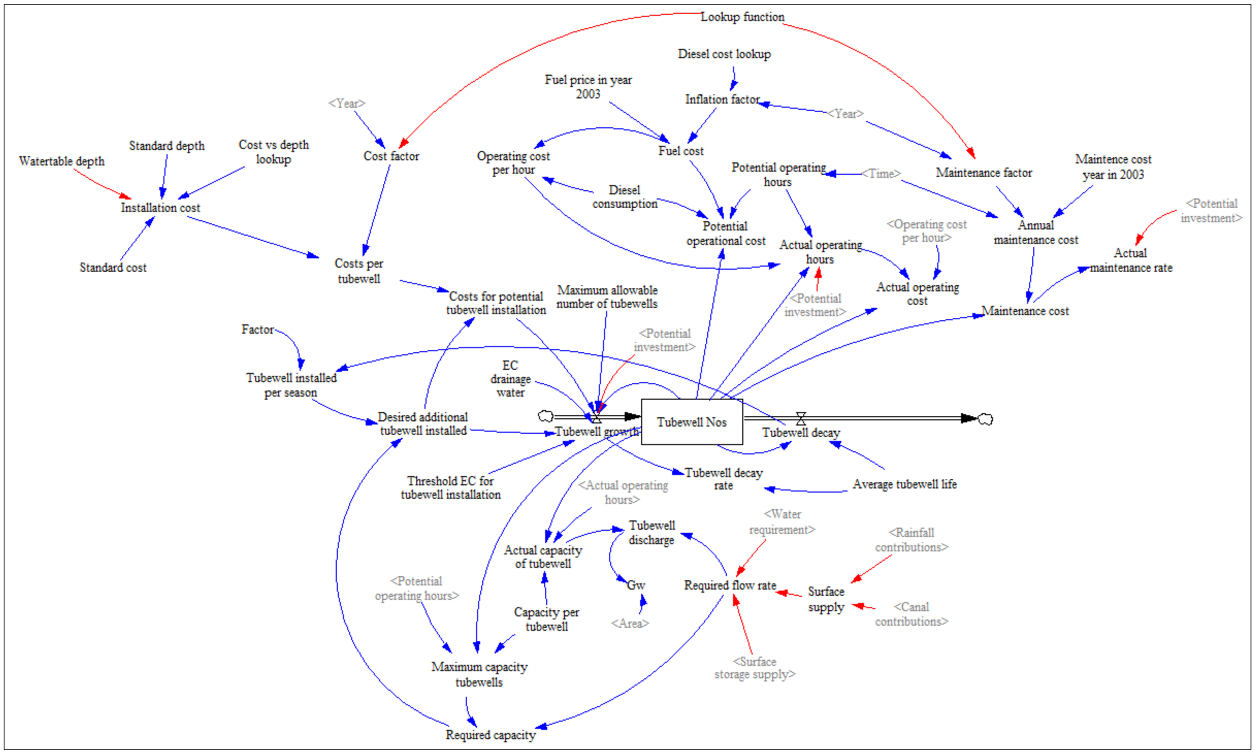


Figure 4.7. Groundwater abstraction sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

According to *Qureshi et al.* [2003], the maximum density of tubewells (at time = 0 i.e. year 1990) in the light rainfall areas of Rechna Doab is about 43 hectares/tubewell (10 tubewells per polygon). This value was used as the initial tubewell stock value and dynamic growth was simulated through inflows and outflows of growth and decay, respectively.

Tubewell Growth Control

The tubewell growth inflow was controlled through potential investment, groundwater quality and water table depth. SAHYSMOD (P component) simulates changes in water table depth and groundwater quality on a seasonal basis and exchanges it with the GBSMD in Vensim. The tubewell growth control function is summarized in Equation 4.15:

$$TWG_p = \begin{cases} WTD_p \leq 12 & \\ EC_{dw_p} \leq 2 & \\ TWC_p < PIN_p, & DATW_p > 0 \\ otherwise, & DATW_p = 0 \end{cases} \quad (4.15)$$

Where TWG_p is tubewell growth in polygon p (no. season^{-1}), WTD_p is water table depth (m), EC_{dw_p} is electrical conductivity of groundwater (dS m-1), TWC_p is tubewell installation cost ($ well^{-1}), PIN_p is estimated potential investment for polygon p ($ season^{-1}), and $DATW_p$ is the desired additional tubewells installed in polygon p. A tubewell will be installed only if there is a shortage in irrigation supply and all of the following three conditions are fulfilled:

1. **Groundwater quality is good**: This assumption is not realistic since 70% of tubewells in the Indus basin are in saline zones [*Shafiq and Saleem*, 2013], but may be helpful in suggesting effective policies for land resources sustainability. The groundwater quality standard was fixed at 2 dS m^{-1} as per the irrigation water quality standard criteria suggested by *Bauder et al.* [2011]. Contributions from tubewells were restricted when the electrical conductivity value of groundwater exceeds 2 dS m^{-1} in areas with no canal water supply. However, for areas under canal command, threshold EC values were optimized for average canal supplies using a conjunctive water use module (Section 4.4.2.1).
2. **Farmers have sufficient resources for tubewell installation**: The crop yield and income sub-model (Section 4.4.2.2) calculates farmer income at each time-step and installs tubewells only if the farmer has sufficient resources. The average installation cost of a diesel or tractor operated tubewell is about 500 USD (around 52,000 Pakistani rupees).
3. **Water table depth is within the economic zone of pumping**: In a study conducted in this study area, *Qureshi et al.* [2003] reported that tubewell installation and operational costs increase exponentially when the water table drops below 12 m (diesel tubewells) [*Qureshi et al.* 2003]. Hence, 12 m was considered to be the economic installation depth for tubewells, and tubewell growth was restricted when water table depth exceeds 12 m.

Additional tubewell capacity was estimated through a goal seek function; the difference in installed capacity and required flow rate determine desired capacity. Since the use of large capacity tubewells installed under SCARP (Salinity Control and Reclamation Program) projects has been discontinued due to high operational costs, the tubewell capacity of one cusec (0.028 m^3 sec^{-1}) as reported by many researchers [*Qureshi et al.* 2003; *Ertsen and Kazmi,* 2011] was considered. A majority of stakeholders also reported the same capacity during interviews. Tubewell discharge estimated in the GBSDM – through actual operating hours and the number of tubewells was used as groundwater extraction in SAHYSMOD (P component) to simulate changes in groundwater levels.

Decay Rate

Average tubewell life was assumed to be 10 years or 20 crop seasons [*Mangrio et al.* 2015]. Decay rate was estimated through a delay function in which the tubewell decay rate becomes equal to growth rate after a delay in average tubewell decay time.

Operation and Maintenance Cost

The average annual repair and maintenance costs of a private diesel tubewell are about 75 USD [*Qureshi et al.* 2003]. Average fuel consumption for diesel-operated tubewell engines varies from 1.5 to 2.5 liters per hour [*Qureshi et al.* 2003]; the product of fuel consumption and fuel price was used to estimate the per hour operating costs of a tubewell. Groundwater extraction was estimated through the utilization factor of private tubewells reported in the literature for the study area [*Qureshi et al.* 2003]. The utilization factor was defined as the ratio of tubewell operational hours in a year to total number of hours in a year, and depends upon the tubewell type, cropping season, energy prices and water market. For the study area, *Qureshi et al.* [2003] reported utilization factors of 6.15% and 11.36% for the winter and summer seasons, respectively. It was estimated that a private tubewell usually operates 6 hours per day, for 56 days in the winter season and 83 days in the summer season [*Qureshi et al.* 2003]. An inflation lookup or table function defined through reports of the Statistical Bureau of Pakistan from 2003 was used to project reported costs for other years of simulation periods. Tubewell operations were further constrained by the availability of economic resources. Hence, actual operating hours and costs were calculated through potential investments in Equations 4.16 and 4.17 (See Section 4.4.2.2):

$$OC = FC \times DC \tag{4.16}$$

$$AOH_p = \max\left(\frac{PIN_p}{(OC \times TWN_p)}, 0\right) \tag{4.17}$$

$$AOC_p = \ AOH_p \times TWN_p \times OC \tag{4.18}$$

Where OC is operating cost (\$ hr^{-1}), FC is fuel cost (\$ liter^{-1}), DC is diesel consumption (liters hr^{-1}), AOH_p is actual operating hours in polygon p (hrs season-1 no.$^{-1}$), TWN_p is the total number of tubewells in polygon p, and AOC_p is actual operating cost. Values of AOC_p estimated through Equation (4.18) were used in the economic module for estimating farmer expenditure.

Net Available Water

Water supply comes from different sources (e.g. canal, rainfall, groundwater abstraction, surface storage) and was further constrained by the availability of surface storage volume and groundwater exploitation capacity. Figure 4.8 shows the structure of the water availability module. Equation (4.19) describes the dynamics of available water stock:

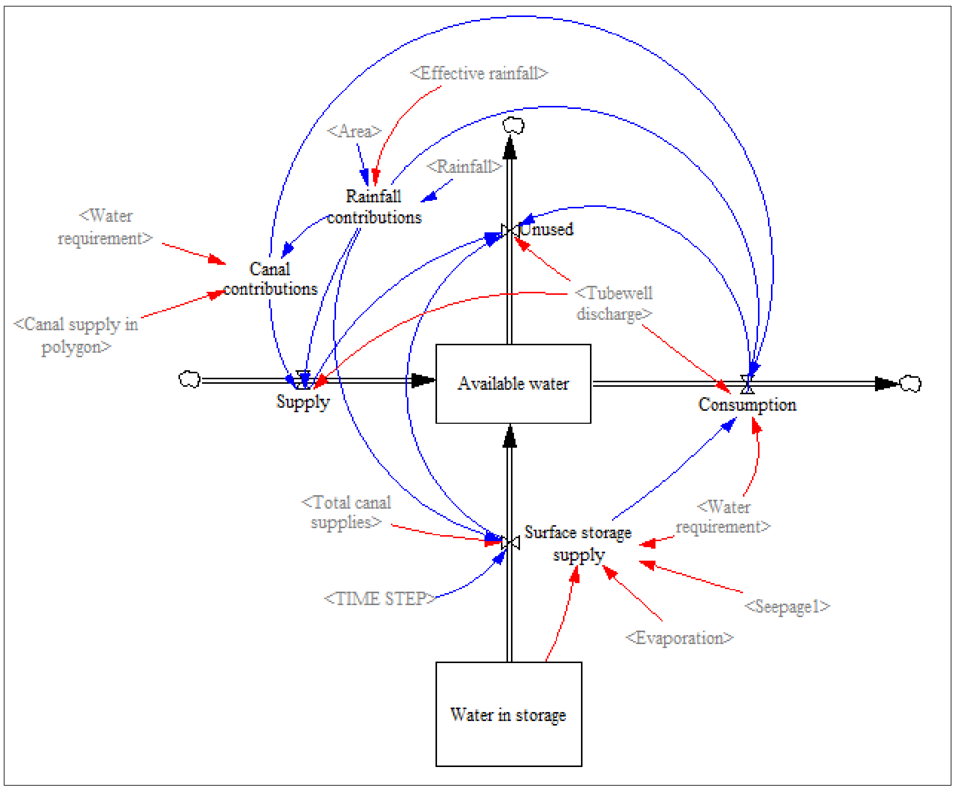


Figure 4.8. Water availability model structure. Note: Red arrows indicate feedback links.

$$\big(AW(t)\big)_p = \big(AW(t_0)\big)_p + \int_0^t \big((RC)_p + (CS)_p + (SS)_p - (SD)_p - (AC)_p\big) \qquad (4.19)$$

Where $AW(t)_p$ and $AW(t_o)_p$ are available water at start and end time t, respectively, in polygon p. Estimation of RC_p, CS_p, and SS_p have been described earlier. SD_p is surface drainage outflow (m^3 season^{-1}), which is considered to be water in excess of crop water demand, and AC_p is agricultural water consumption (m^3 season^{-1}) in polygon p. It is described in Equation 4.20:

$$(AC)_p = \max\left((CS)_p + (RC)_p + (SS)_p + (TWD)_p, (ET_c)_p\right) \tag{4.20}$$

ET_{cp} has been described earlier in this paper. The model structure was based on a demand-based irrigation system (i.e. first runoff was used to satisfy the irrigation demand). In cases of insufficient supply of rainfall water, attempts will be made to satisfy demand with canal supplies. If runoff and canal supplies both fail to fulfill demand, water in surface storage will be utilized. Finally, if all surface resources fail to meet crop demand, groundwater will be extracted. This is represented as TWD in Equation 4.20. During the first phase of the present study [*Inam et al.* 2015], farmers supported this assumption by stating that, due to high pumping costs, they pump groundwater only when there is a shortage of surface water.

4.4.2.4 Management Module

The management module includes surface storage/ponds, canal lining, and modern irrigation techniques as management options. These options were included as per the recommendations of stakeholders (i.e. local farmers, academic experts, government officials, NGOs, management institutes, etc.) [*Inam et al.* 2015]. The quantification details of the management sub-models are described below.

Surface Water Storage Sub-model

Surface storage ponds are used to store excess water during wet years and provide it during periods of low flows. Figure 4.9 shows the structural details of the surface water storage sub-model. The main stocks are constructed capacity (m^3), silted capacity (m^3), water in storage (m^3), and AW (water diverted from the storage) (m^3).

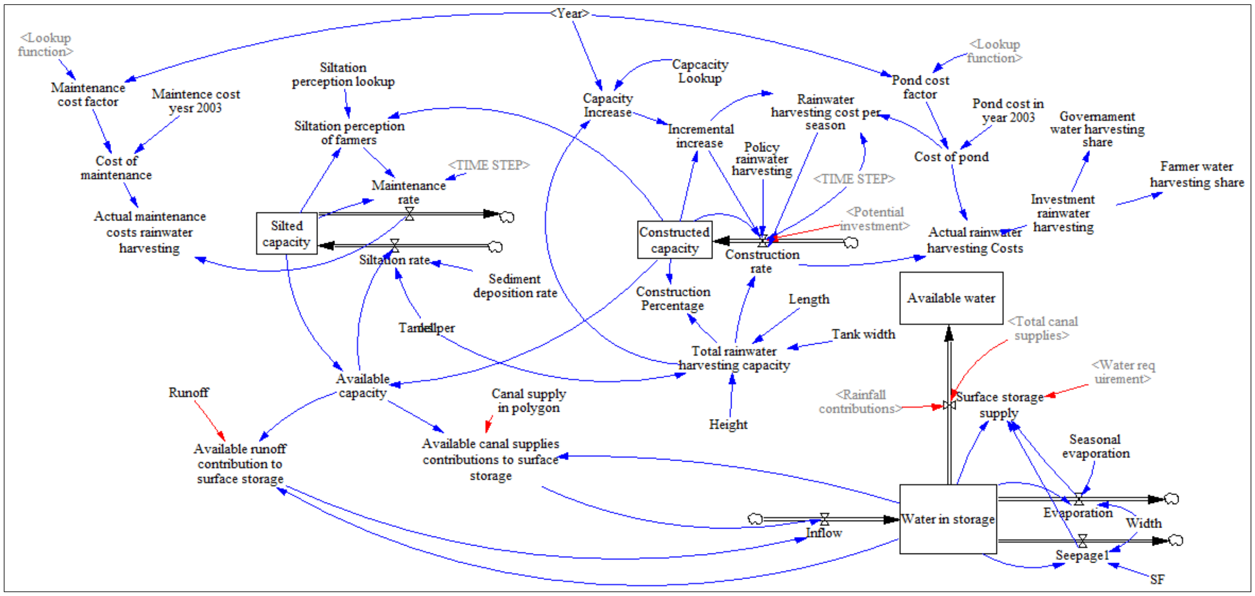


Figure 4.9. Surface water storage sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

Constructed Capacity

Chughtai and Mahmood [2012] conducted research in the study area to assess the feasibility of semi-intensive carp culture. This was the only study available with earthen ditches design and economic details in the study area. The size and density of earthen ditches per polygon were assumed according to their recommendations:

$$WHC = N \times V \tag{4.21}$$

Where *WHC* is water harvesting capacity (m^3), *N* is the number of water storage ponds per polygon (dimensionless) and *V* is the storage volume of a single pond (m^3). A goal seeking objective function proposed by *Sterman* (2000) was used to simulate the dynamics of the constructed capacity stock. For the simulation period, future water harvesting policy was defined through a capacity lookup function for each polygon, which provides control to give more weight to downstream areas. At each time-step, the model evaluates the discrepancy between total and desired capacity and recommends incremental increases, if required. The construction rate was controlled by the following factors:

1. **Constructed capacity is less than desired capacity**: As per recommendations by local stakeholders and experts (see *Inam et al.* [2015] for details), it was assumed that a farmer

uses 10% of their land for constructing rainwater harvesting ponds. Construction of further storage was restricted when a desired level of storage is achieved.

2. **Farmers have sufficient resources for pond construction**: The economics module (See Section 4.4.2.2) calculates farmer income at each time-step and limits construction of further storage if the farmer does not have sufficient resources. Construction cost details reported by *Chughtai and Mahmood* [2012] for the study area were used to calculate the per unit cost ($\$$ $^{m-3}$) of surface water storage. The dynamics of the constructed capacity stock are summarized in Equations (4.22) and (4.23):

$$CRC_p = \begin{cases} CC_p \leq DC_p & \\ WHC_p < PIN_p, & CR_p > 0 \qquad CR_p \\ \quad otherwise, & CR_p = 0 \end{cases} \quad = \frac{(C_{Incre})_p}{\Delta T} \tag{4.22}$$

$$\big(CC(t)\big)_p = \big(CC(t_0)\big)_p + \int_0^t CR_p \times dt \tag{4.23}$$

Where CRC_p is construction rate control, DC_p is desired capacity (m^3), *WHC* is water harvesting cost ($\$$ season^{-1}), PIN_p is estimated potential investment ($\$$ season^{-1}), CR_p is construction rate for polygon p (m^3 season^{-1}), C_{incre} is incremental increase in capacity (m^3) as defined through the lookup or table function, ΔT is time-step (season), and CC_p is constructed capacity – or total available capacity – for polygon p. The product of construction rate (m^3 season^{-1}) and cost of storage per unit volume ($\$$ m^{-3}) estimates water harvesting expenses ($\$$ season^{-1}). In Pakistan, such projects are usually designed based on private-public partnerships, where a 75% share comes from the government and 25% comes from beneficiaries. The calculated water harvesting share of farmers was used to estimate expenditure in the income sub-model (see Section 4.4.2.2).

Silted Capacity

Constructed storage capacity gets silted with time and results in a loss of storage volume. The dynamics of the silted capacity stock are summarized in Equations (4.24) - (4.26):

$$\big(SC(t)\big)_p = \big(SC(t_0)\big)_p + \int_0^t (SR_p - MR_p) \times dt \tag{4.24}$$

$$MR_p = \frac{SC_p}{\Delta T} \times SPF_p \tag{4.25}$$

$$SPF_p = \frac{SC_P}{CC_P} \tag{4.26}$$

Where SC_p is silted capacity (m*3*), SR_p is silt deposition rate (m^3 $season^{-1}$), MR_p is maintenance rate (m^3 $season^{-1}$) for polygon p, and SPF_p is the siltation perception state of a farmer (dimensionless) and is a function of silted capacity and constructed capacity of polygon p (Equation (4.26)). The dynamics of the perception state was achieved through a lookup or table function. The perception state of a farmer acts as a lever and activates the maintenance function when 25% of constructed capacity has been silted up. The perception state was a policy option and can be modified as per site investigations and stakeholder interviews.

Many factors such as vegetative cover, soil type, and slope affect the sediment deposition rate. The estimation of sediment deposition rate was beyond the scope of this study, however, a siltation rate of 0.021 m^3 $season^{-1}$, as reported by *Arshad* [2004] for the study area, was used. Maintenance cost estimation procedures were the same as discussed in the constructed capacity part of this section.

Water in Storage

This stock controls the dynamics of diversion to and diversion from the constructed storage. Gross available storage per polygon was estimated through the difference in constructed and silted capacities estimated by Equations (4.23) and (4.24), respectively. Runoff and excess canal supplies in periods of low crop water requirements were considered to be the main sources of water diversions to storage.

At each time-step, the model calculates the net available volume of storage using the difference in gross available storage and water-filled storage. Water was diverted from the source only if sufficient storage volume was available, otherwise, the excess supply was considered to be lost. Dynamics of the water in storage stock are represented in Equations (4.27) - (4.30):

$$\big(WS(t)\big)_p = \big(WS(t_0)\big)_p + \int_0^t (INF_p - E_p - S_p - Out_p) \times dt \tag{4.27}$$

$$INF_p = RO_p + C_p \tag{4.28}$$

$$E_p = SA \times SE \tag{4.29}$$

$$S_p = WP \times SF \tag{4.30}$$

Where *WSp* is available water in storage (m^3), INF_p is inflow to surface storage (m^3 season^{-1}), RO_p is runoff contribution (m^3 season^{-1}), C_p is excess canal supply contribution (m^3 season^{-1}), *Ep* is evaporation losses from surface storage (m^3 season^{-1}), *SA* is surface area (m^2), *SE* is open surface evaporation (m season^{-1}) (calculated from metrological data, described in detail in *Ward and Trimble* [2003]), S_p is seepage loss (m^3 season^{-1}), *WP* is wetted perimeter (m^2) and *SF* is the seepage factor (m^3 season^{-1} per m^2 of wetted area). A seepage factor of 0.005 m^3 season^{-1}, as reported by *Arshad* [2004] for the study area, was used. Out_p is regarded as the outflow from the surface storage for polygon *p*. It was controlled on the basis of demand-based irrigation rules. The decision control of diversions from surface storage can be summarized in Equation 4.31:

$$SS_p = \begin{cases} (ET_c)_{i,p} - (RC)_p - (CS)_p & (ET_c)_{i,p} > (RC)_p + (CS)_p \\ 0 & (ET_c)_{i,p} < (CS)_p \end{cases} \tag{4.31}$$

Where *SSp* is the surface storage supply in polygon *p* (m^3 season-1) on the basis of demand-based irrigation.

Canal Lining and Seepage

Percolation from the irrigation network was considered to be the primary cause of waterlogging problems in saline zone areas. Canal lining serves two purposes; firstly, it helps in the conservation of precious surface water resources; secondly, it reduces the risk of waterlogging. In a research study in Rechna Doab, Pakistan, *Arshad* [2004] concluded that, on the average, 38% of diverted discharge in irrigation networks is lost as seepage, and canal contribution is 57% of the total recharge. This seepage volume might be saved with effective canal lining programs. However, lining is expensive and needs proper justification in terms of volume saved, area reclaimed, crop growth and yield increased. Figure 4.10 shows the structure details of the canal lining and seepage sub-model.

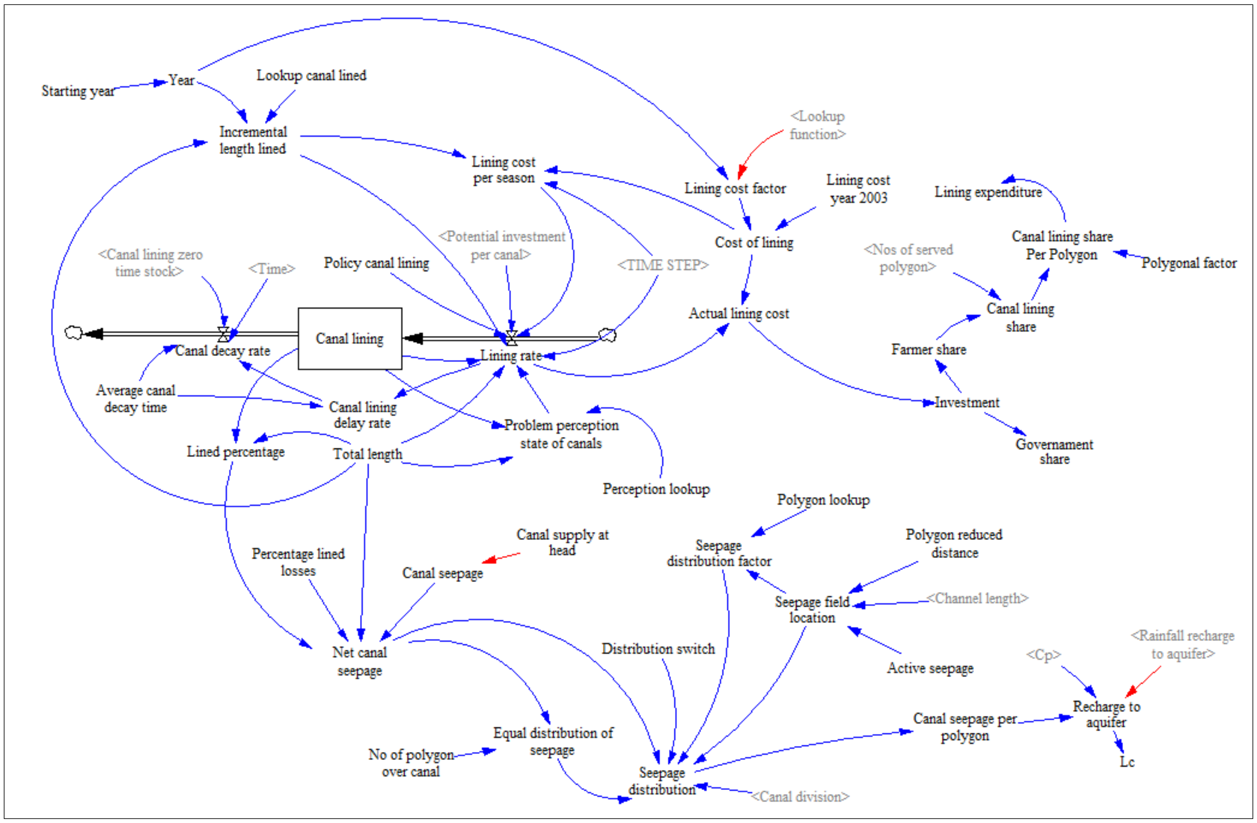


Figure 4.10. Canal lining and seepage sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

In the first phase of the current study [*Inam et al.* 2015], the authors observed two different schools of thought regarding government canal-lining programs. The first group of stakeholders (government departments, research organizations, NGOs) praised the government for Pakistan's lining programs in terms of their water saving ability, while the second (farmers, water boards) considered them obstructions to aquifer recharge and showed resistance to the policies in the broad interest of aquifer sustainability. Hence, evaluation of this policy with an integrated model is important in order to judge the long-term sustainability of the aquifer.

The main stock was canal lining, which controls the dynamics of the lined percentage of total canal length, as shown in the following equation:

$$\left(CL(t)\right)_c = \left(CL(t_0)\right)_c + \int_0^t (LR_c - DR_c) \times dt \tag{4.32}$$

Where CL_c is canal lining length for canal c (m), LR_c is lining rate (m season^{-1}), and DR_c is decay rate (m season^{-1}). The difference in lining and construction rates at any time t estimates the increase or decrease in canal lining stock. A canal lining policy switch was created whose values can vary between 0 (no lining) and 1 (canal lining). Desired canal lining goals were created through a lookup or table function. Incremental increases in length were estimated through a goal seeking function [*Sterman*, 2000]. The cost of canal lining was estimated through the same procedure as discussed in the water storage sub-model. The 25% share owed by beneficiaries is distributed on a polygonal basis by using the following relationship:

$$CLS_{c,p} = \frac{FS_c}{NP_c} \tag{4.33}$$

Where $CLS_{c,p}$ is the beneficiaries' canal lining share of polygon p for canal c (\$ season^{-1}), FS_c is the total farmer share of canal c (\$ season^{-1}), and NP_c is the total number of polygons irrigated by canal c (dimensionless). Average canal decay time was assumed to be 5 years (10 seasons) [*Arshad*, 2004]. Canal seepage was estimated through an empirical relationship proposed by a Punjab groundwater development project consultant [*Arcadis-Euroconsult and NDC*, 1998].

$$S_c = 4.27\times\ {Q_c}^{0.658} \tag{4.34}$$

Where S is seepage in $m^3\ s^{-1}\ mile^{-1}$ and Q is canal discharge in $m^3\ s^{-1}$. Recharge estimates for unlined canals in Equation (4.34) are reduced for lined portions of canal length. Net canal seepage can be summarized as follows:

$$NCS_c = S_c\times\Big(TL_c - \big(LP_c\times TL_c\times(1-LLP)\big)\Big) \tag{4.35}$$

Where NCS_c is net canal seepage for any particular canal c (m^3 season^{-1}), TL_c is total length (m), LP_c is lined percentage estimated through the ratio of lined length (stock) to total length (dimensionless), and LLP is percentage seepage loss for the lined portion of canal c. Percentage lined losses were assumed to be 0.2 percent of total unlined seepage losses [*Arshad,* 2004]. Net seepage volume over the complete canal length was distributed on a polygonal basis using a similar model structure and mathematical equations as described in the irrigation distribution and application sub-model (see Section 4.4.2.3). Only those polygons through which the canal is passing were considered in the estimation of distribution factors. Upstream and downstream seepage weights were defined using polygon location over the canal length. Polygonal seepage estimation was exchanged with SAHYSMOD (P component) as L_c (deep percolation losses). Canal lining was limited by availability of funds and the perception state of the canal.

Irrigation Efficiency

Irrigation efficiency depends entirely on the method of irrigation. Commonly reported irrigation efficiencies for flood, sprinkler and drip irrigation methods for Pakistan are 62%, 81% and 90%, respectively [*Shaikh et al.* 2015]. Figure 4.11 shows structural details of the irrigation efficiency sub-model.

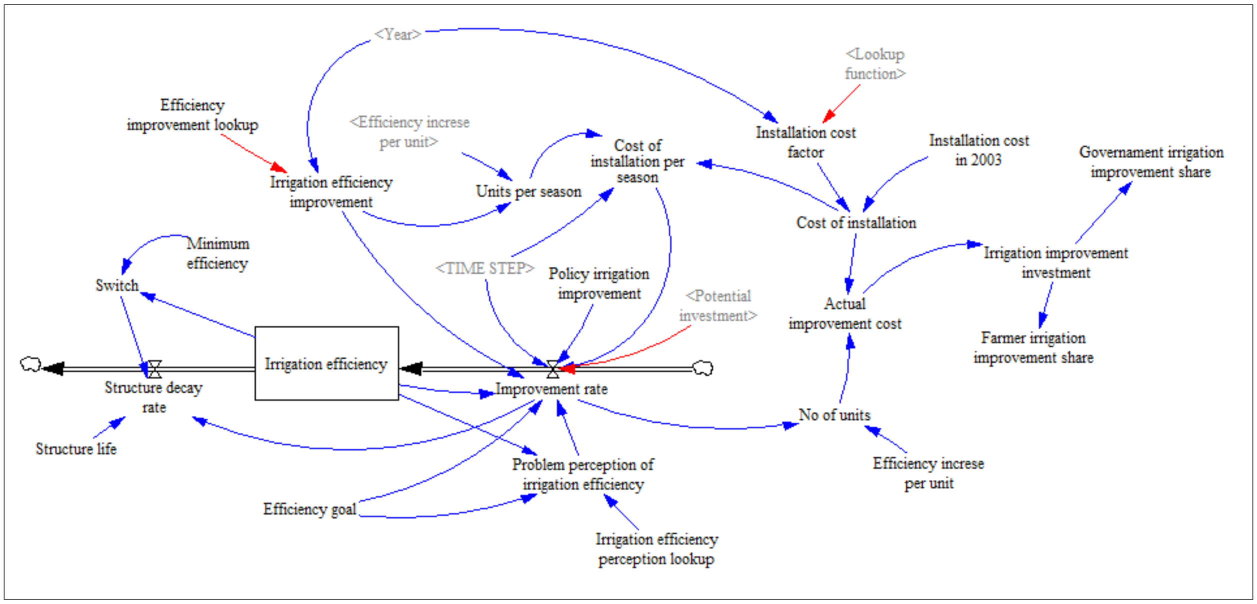


Figure 4.11. Irrigation efficiency sub-model. Note: Red arrows indicate feedback links. See Figure 4.12 for feedback details.

Flooding was the most commonly used irrigation method in the study area. Therefore, 62% was used as the minimum irrigation efficiency and a controlling switch is provided which prevents the irrigation efficiency stock from going below 62% by assigning a zero decay rate whenever efficiency equals the minimum limit as shown in Equation (4.36):

$$Switch_p = \begin{cases} Irrigation\ \ efficency_p > 0.62 & 1 \\ Irrigation\ \ efficency_p \leq 0.62 & 0 \end{cases} \tag{4.36}$$

Life expectancy of irrigation structures (drip and sprinkler) was fixed as 15 years, or 30 seasons [*Lamm and Trooien,* 2003], and the structure decay rate was estimated through a delay function. The irrigation efficiency goal was fixed at 90% (based on the drip irrigation technique) and a goal seeking objective function [*Sterman,* 2000] was used to estimate incremental increases in irrigation improvement at each time-step. A policy switch was created and values could vary between 0 (No improvement) and 1 (Irrigation structure improvement). Annual irrigation efficiency improvement goals were created through a lookup or table function. Numbers of drip and sprinkler irrigation units installed per season were estimated by taking the ratio of improvement rate to efficiency increase per unit, considering that a full-sized sprinkler irrigation system unit can serve an area of 50 hectares [*Lamm and Trooien,* 2003]. The installation price of a single unit in Pakistan was assumed to be 131000 USD (approximately 13600000 Pak rupees), as per the recommendations of *Iqbal and Iqbal* [2015]. Due to high investment costs, poor economic conditions of farmers and small farm sizes in Pakistan, adaptation of advanced irrigation methods does not initially seem feasible, however, with declining water resources, pressurized irrigation technology may be significant [*Qureshi,* 2011; *Iqbal and Iqbal,* 2015]. In order to increase the adoptability of micro irrigation systems, the government is providing subsidies to cover 80% of the cost. The remaining 20%, which includes labor, must be paid by the farming community. Therefore, this cost distribution ratio was used to estimate government and farmer irrigation improvement shares. Irrigation efficiency improvement was limited by the availability of funds.

4.4.3 Integrated Model Component Feedbacks

The integrated model with interchanging processes/variables and feedbacks between SAHYSMOD (P component) and Vensim DSS (GBSDM) sub-models is represented by a simple casual loop diagram, shown in Figure 4.12. The GBSDM transfers values of seepage, irrigation application, groundwater extraction and application efficiency to SAHYSMOD and takes values of cropped area, water table depth, groundwater quality, drainage volume, and root zone salinity from SAHYSMOD.

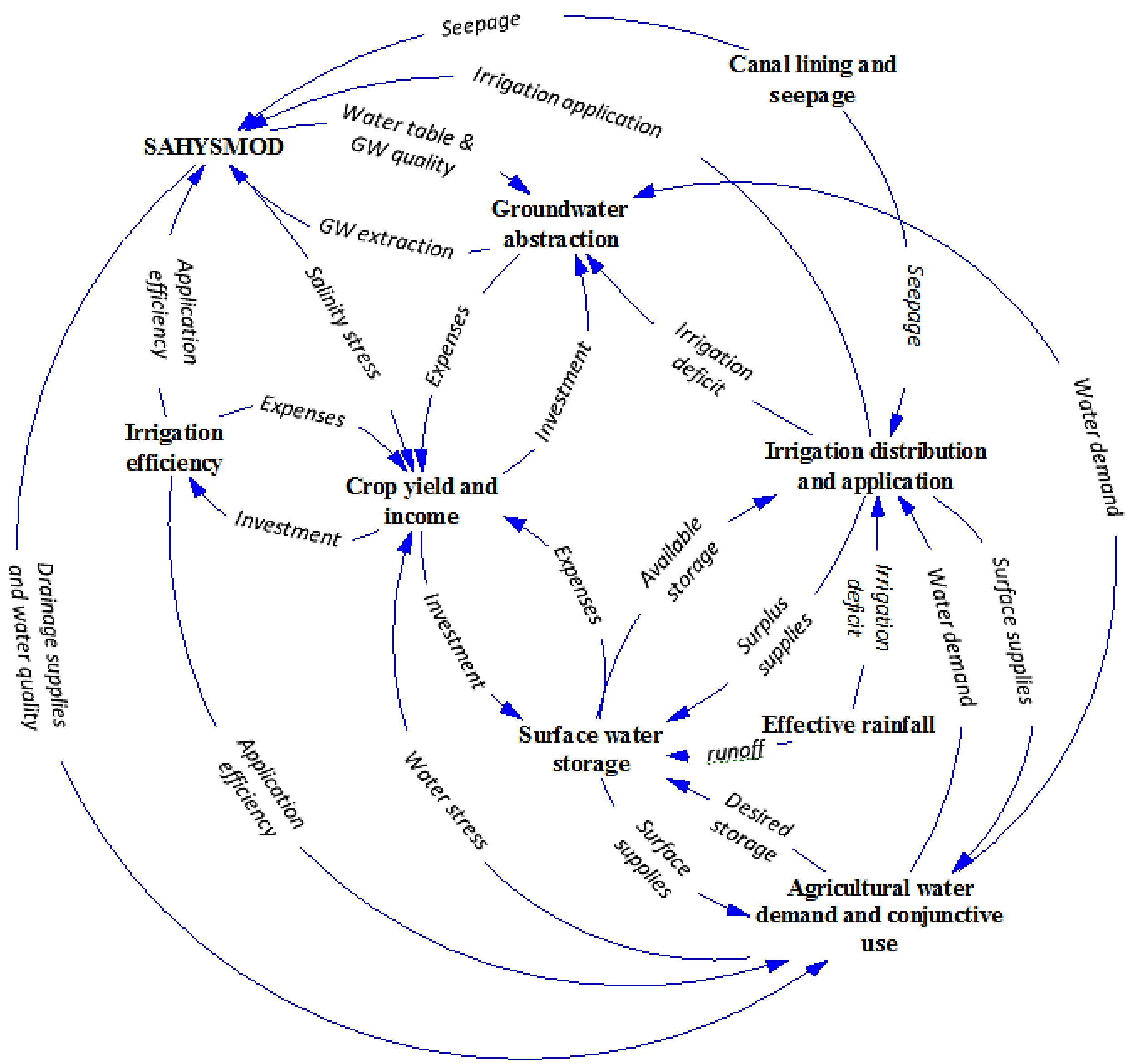


Figure 4.12. Integrated model feedback structure. Note: variables in bold represent sub-modules of the integrated model. See section 4.4.2 for details.

All sub-models of the GBSDM represent individual processes (sub-model names are represented in *italics*). For example, the *canal lining and seepage* sub-model estimates seepage losses on a polygonal basis and then imports this information into the *irrigation distribution and application* sub-model to estimate the net available water after losses. Similarly, the *effective rainfall* sub-model estimates runoff and effective rainfall and exports the estimated values to the *surface water storage* and *irrigation distribution and application* sub-models to calculate the desired goals of constructed storage and irrigation deficiencies. Estimations of irrigation supplies from different sub-models were used in the *agricultural water demand and conjunctive use* sub-model to calculate water stress for the *crop yield and income* sub-model, which calculates actual crop yield. Similarly, investments into operation and maintenance – in addition to capital costs estimated in irrigation structure sub-models – were used to calculate expenditures in income modules, and investments estimated from income modules were used to limit improvement and construction rates of irrigation structure sub-models. Each sub-model represents a separate unit and can be used in other SDM studies of a similar nature for integrated modeling processes.

4.5 Physical (P) and SDM (GBSDM) Model coupling

The purpose of model integration in this study was to combine local knowledge (using the GBSDM) and expert knowledge (using the physical SAHYSMOD model) to analyze different scenarios of systems management in a participatory and integrated manner. Model integration is often considered a non-trivial task because of different programming languages, spatial and temporal scales and conceptual frameworks of modeling platforms. Model coupling in the field of SDM remains a challenging task; very few studies of this nature exist. *Prodanovic and Simonovic* [2007] address issues of incorporating socio-economic issues and impacts by coupling hydrological and socio-economic models in the Upper Thames River Basin, Canada for climate change impact assessment. They used a solid set approach by translating both models into Java language. In addition, this type of coupling approach limits model usefulness for local stakeholders since its modification requires significant expertise in Java programming. This type of approach was developed without relevant stakeholder engagement in model design and thus does not explicitly consider local stakeholders' views and perceptions regarding the problem being addressed, the causes of the problem, consequences of the problem, feedback loops, future strategies, etc. In addition, to date, no system dynamics studies anywhere in the world have attempted to include stakeholders' perceptions and socio-economic issues in soil salinity modeling processes. The present study is the first of its kind to explore this topic.

The model coupling approach used in this research study was based on loose coupling (using a complete physically based model as a black box). The physically based model (i.e. SAHYSMOD) and the system dynamics model (i.e. GBSDM) are coupled by using MS Excel as a 'wrapper'. This framework was designed to accommodate the easy migration of the existing physical modeling system (i.e. SAHYSMOD) since its reimplementation may not be economically feasible due to the large investments that have been put into the development and testing of

SAHYSMOD. Figure 4.13 shows the model coupling configuration between both models in this study.

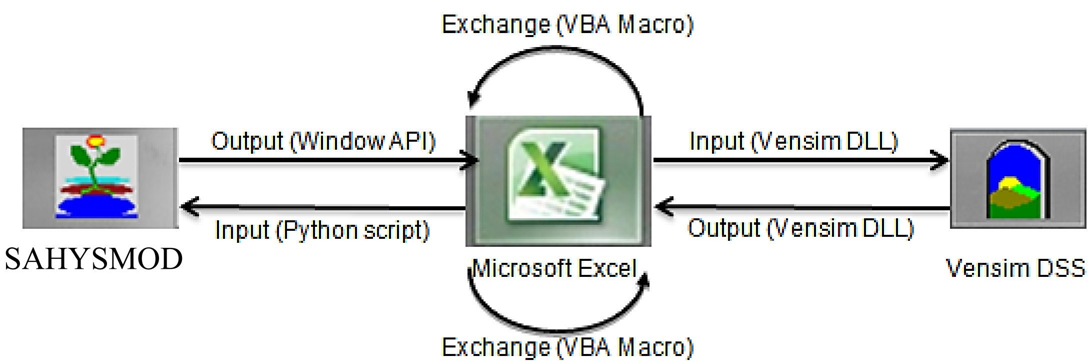


Figure 4.13. Model coupling configuration with programming methods used

The main steps of model coupling in this study were as follows:

- Inputs and outputs of the system dynamics model (i.e. GBSDM) were imported and exported, respectively, to MS Excel using the built-in dynamic link library (DLL) in Vensim DSS.
- The physically based model, SAHYSMOD, was simulated in MS Excel using a SAHYSMOD simulation console.
- Dynamic feedbacks between both modeling platforms were achieved by exchanging input and output at the end of each season through Visual Basic for Applications (VBA) (i.e. MS Excel's macros).
- Finally, Python script was used to create SAHYSMOD input files from MS Excel (.csv) for the subsequent year's simulation.

Model coupling procedures, scripts and code are described in detail in a companion paper (Part II: model coupling and application). Coupling a commonly-used MS Excel environment with an easily amendable Vensim environment can help increase model application, even for non-programming users in developing countries.

4.6 Model Testing and Evaluation

Model testing is an important process in terms of building confidence that the model is acceptable for its intended use. Conventional modeling systems (mechanistic, stochastic, and empirical models) apply statistical methods (e.g. RMSE, NSE, R^2, ME etc.) to test model performance [*Moriasi et al.* 2012]. However, due to the nature of the integrated model developed in the current study (i.e. that an important part of it – the GBSDM – is a group-built system dynamics model), conventional statistical model testing procedures are difficult to apply because of the following reasons [*Barlas,* 1989]:

- Noise is not necessarily independent and normally distributed. Due to high auto-correlation and non-stationary means and variances, system dynamics predictions violate the rules necessary for standard statistical tests.
- System dynamics models do not predict individual values of output variables, rather they predict time patterns or trends. Hence, model testing tools for system dynamics type models should be based on pattern evaluation rather than on point to point evaluation.
- Statistical methods such as R^2 are not appropriate for system dynamics models because they measure point to point discrepancies between predicted and real behaviour.

A model testing framework based on procedures described in the system dynamics model literature [*Barlas,* 1989; *Sterman,* 2000; *Qudrat-Ullah and Seong,* 2010] was thus used to test the coupled P-GBSDM. The testing procedure consisted of the structure validity and behavior validity tests. These tests are widely considered to be useful for testing system dynamics models [*Qudrat-Ullah and Seong,* 2010]. The overall model testing process is illustrated as a flowchart in Figure 4.14, while the details of each step are as follows.

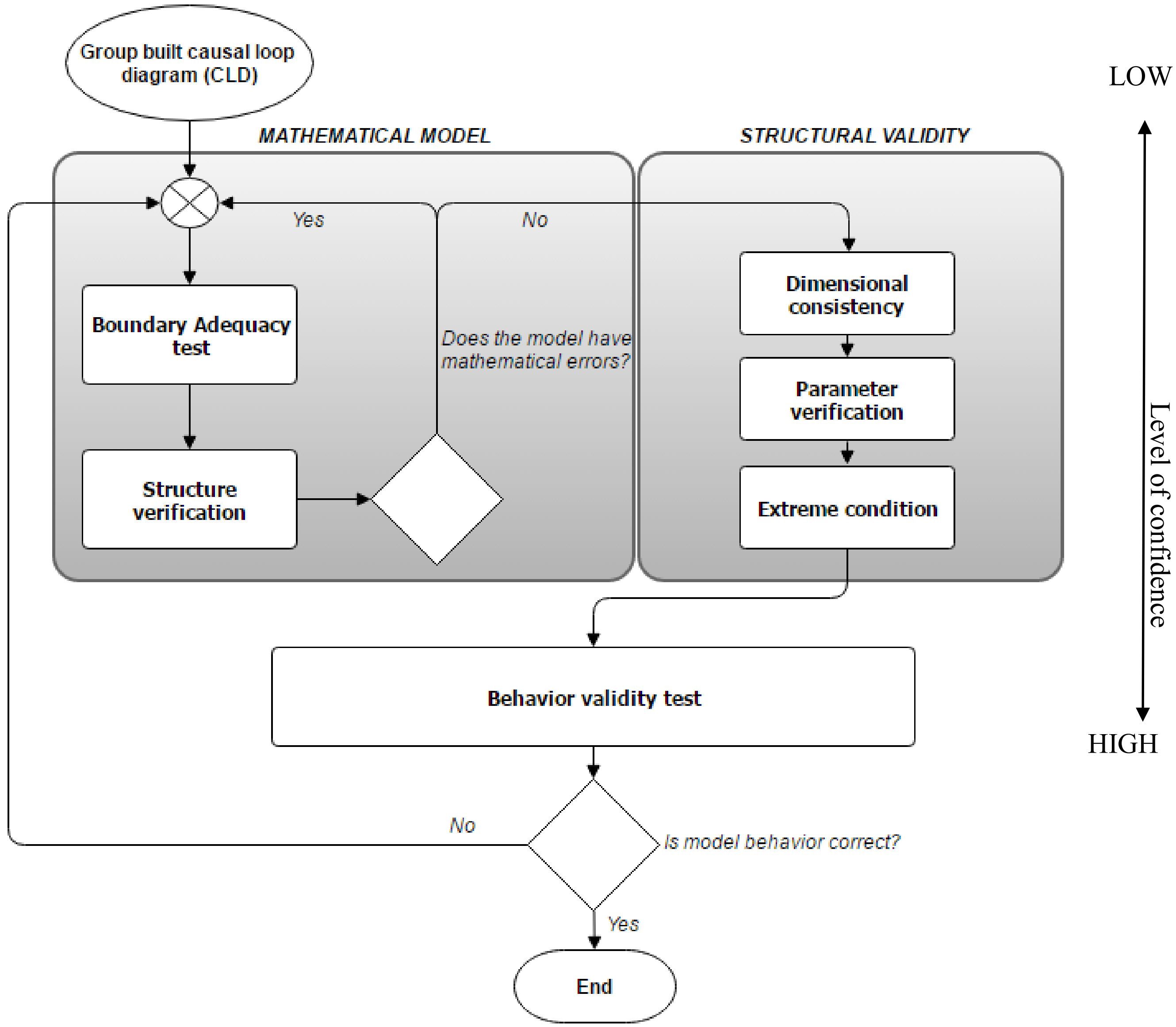


Figure 4.14. Model testing procedure with steps of structure and behaviour validity tests

Figure 4.14 describes model testing as an iterative process. After the group built qualitative models were developed by the stakeholders, causal loop diagrams were classified for exogenous and endogenous processes for boundary adequacy. In the next step, submodules of different processes were developed and their output and structure was verified with published data and reports. Different submodules were linked and the complete model structure was checked for any mathematical errors. In the case of any errors, mathematical, boundary adequacy and structure verification were refined. In the case of no error, structure validity followed by behavior validity tests were performed. Structural validity tests were important for checking model structural errors.

These tests were performed by subjecting the model to parameter verification, dimensional consistency and testing under extreme conditions. Behavior validity tests checked model behavior and ensured that the models are producing acceptable output behavior.

Both tests consist of a number of steps that should be applied in a logical order. Structural validity tests should be performed before behavior validity tests because parameter combinations of a complex system may produce numerous behavior patterns, some of which may be close to real behavior, even with structurally incorrect models. *Qudrat-Ullah and Seong* [2010] and *Barlas* [1989] discuss in detail the processes of structural and behavior validity tests for system dynamics models. The following section mainly focuses on applying these steps in a logical order for the P-GBSDM to enhance the overall testing process for building confidence regarding model performance.

Structural Validation

Qudrat-Ullah and Seong [2010] recommend two important stages of structure validation: structure validity tests and structurally-oriented behavior tests. A structure validity test is important for comparing model structure and equations with the available theory, whereas, a structurally-oriented behavior test is important for evaluating the acceptability of model behavior under different conditions.

4.6.1 Structural Validity Test

The structural development of P-GBSDM consists of different stages, such as the development of group-built qualitative Causal Loop Diagram (CLD) models (see [*Inam et al.* 2015] for details), classification of CLDs into different processes, physical model simulations for biophysical changes, quantitative model development of socio-economic components in the form of stock and flow models and coupling of physical and socio-economic models through a component modeling approach. All processes together form a complicated model structure. P-GBSDM structure validation was an iterative process. The structure of the model is continually refined until the model passes all validity tests. The major steps of the structure validity tests are discussed in the following sections.

4.6.1.1 Boundary Adequacy

Boundary adequacy ensures that all of the important processes (e.g. water demand and supply, crop stresses, groundwater extraction, etc.) that have some significance in addressing policy issues (e.g. water reallocation, conjunctive water use, vertical drainage, irrigation methods improvement) have been added endogenously into the model. Figure 4.15 summarizes major exogenous and endogenous processes used in the development of P-GBSDM. This arrangement is based on recommendations from stakeholder interviews [*Inam et al.* 2015]. Feedback from soil salinity experts from different research organizations (International Water Management Institute (IWMI), Directorate of Land Reclamation (DLR), Soil Monitoring Organization (SMO), Punjab Irrigation Department (PID), Water and Power Development Authority (WAPDA)), and stakeholders during the model building process, helped to build confidence in the model boundary adequacy step.

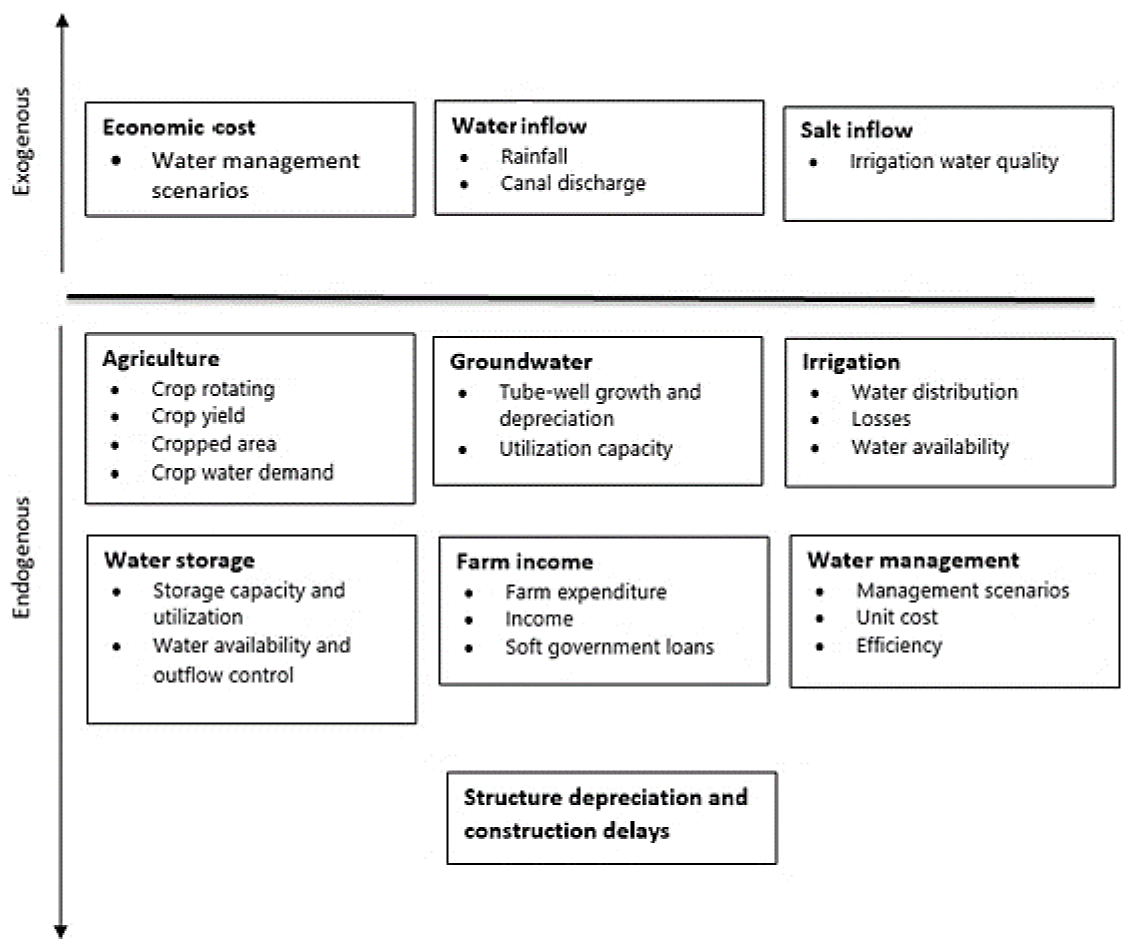


Figure 4.15. P-GBSDM boundary summary

All of the important processes pertaining to the research objective (i.e. soil salinity management) were described as endogenous procedures. Since soil salinity mainly results from a high water table and irrigation with marginal-quality groundwater [*Kazmi et al.* 2012], all water table depth control and conjunctive water quality parameters were defined endogenously within the GBSDM. Groundwater contribution, crop water requirements, irrigation application, and seepage losses were later exchanged with SAHYSMOD (P component). All uncontrolled parameters responsible for water inflow (e.g. precipitation, canal discharge and salt inflow) and subsidies were defined exogenously in the form of time series.

4.6.1.2 Structure Verification

Structure verification is usually considered a main step in the structure validation process [*Qudrat-Ullah and Seong,* 2010]. For structure verification purposes, past implemented project data, published in various project reports, was tested with sub-sections of the model, and reported values were compared with model output. For example, data such as tubewell growth rate reported in a groundwater economy report [*Qureshi et al.* 2003] was used to verify the groundwater development sub-section of the model. Similarly, data reported in *Ullah et al.* [2001] was used to verify the crop water requirement sub-model. In addition to this approach, sections of different system dynamics models available in the existing literature were utilized in formulating the P-GBSDM structure. Details and references for these sections are given in Table 4.2.

Table 4.2. P-GBSDM model structure components from existing literature

Model Structure	Reference	Comments
Crop yield	*Pervin and Islam* [2015]; *Schmitt* [2007]	Model structure formulation is adopted
Effective rainfall and water requirement	*Elmahdi* [2006]	Model structure formulation is adopted
Water storage and supply	*Xi and Poh* [2013]	Model structure formulation is adopted
Irrigation efficiency	*Saysel* [2004]	Model structure formulation is adopted
Salinity stress	*Saysel* [2004]	Model structure formulation is adopted
Water stress	*Pervin and Islam* [2015]	Model structure formulation is adopted
Groundwater development	*Qureshi et al.* [2003]	Formulation and economic details are adopted
Water storage reservoir	*Chughtai and Mahmood* [2012]	Pond design formulation with economic details are adopted.

The other major part of P-GBSDM consists of the physical model, SAHYSMOD (P component). It simulates the physical processes of salt and water movement within the crop root zone. SAHYSMOD has been subjected to evaluation in various studies [*Akram et al.* 2009; *Desta,* 2009; *Liaghat and Mashal,* 2010; *Singh and Panda,* 2012b]. For the current study, the physical model (SAHYSMOD) was also tested through model calibration and validated over the study area. Details of physical model testing are presented in *Inam et al.* [2017a].

To provide details on its structure, the main elements of the P-GBSDM are represented in a simple causal loop diagram (See Figure 4.16) with relationships and feedbacks between different interfacing variables of SAHYSMOD (P) and Vensim DSS (GBSDM). Major processes include: surface water availability improvement, groundwater development, fund allocation, and crop area and yield estimation. Key stocks are: government subsidies, farmer share, irrigation efficiency, surface storage, canal lining, seepage, aquifer, pumping capacity, farmer income, crop yield, cropped area and soil salinity. Feedbacks are represented through reinforcing (R) or balancing (B) loops. Five important feedback loops can be identified in Figure 4.16. The first balancing loop (1B) shows how improvement in monetary resources accelerates overexploitation of groundwater, thus affecting groundwater sustainability; pumping capacity and farmer income act as the limiting factor. Once both of these factors become available, groundwater is ready to be used. The second balancing loop (2B) is a water supply loop, which indicates a balancing effect on water availability. With an increase in water scarcity, farmers try to invest more money in water saving schemes and at the same time, try to increase pumping capacity to meet their water demand from groundwater storage. Loop (1R) indicates the effect of improved supply, which causes an increase in cropped area, thereby increasing farmer concern regarding water shortages. Loop (1B) and (1R) together reflect the interaction between water demand and supply, which displays oscillating behavior. As water stress increases, effective water saving measures (loop 4B) dominate. The outcome of these measures after a delay, depending upon the type of measure, increases water availability. With a decrease in water scarcity, loop (1R) dominates and causes an increase in cropped area, thereby increasing water stress. The third balancing loop (3B) represents the effect of conjunctive water use on the system. Continued abstraction of groundwater increases its proportion in irrigation water supplies, which gives rise to the problem of secondary salinization, affecting farmer income by reducing crop yield. Leaching requirements also reduce water availability and contribute to increasing water stress.

Physical processes such as salt concentration in the root zone, groundwater depth, cropped area and groundwater quality were calculated through SAHYSMOD (P component). Socio-economic measures such as increases in installed capacity of tubewells, canal lining, surface water storage and allocation of funds were controlled in Vensim DSS (GBSDM).

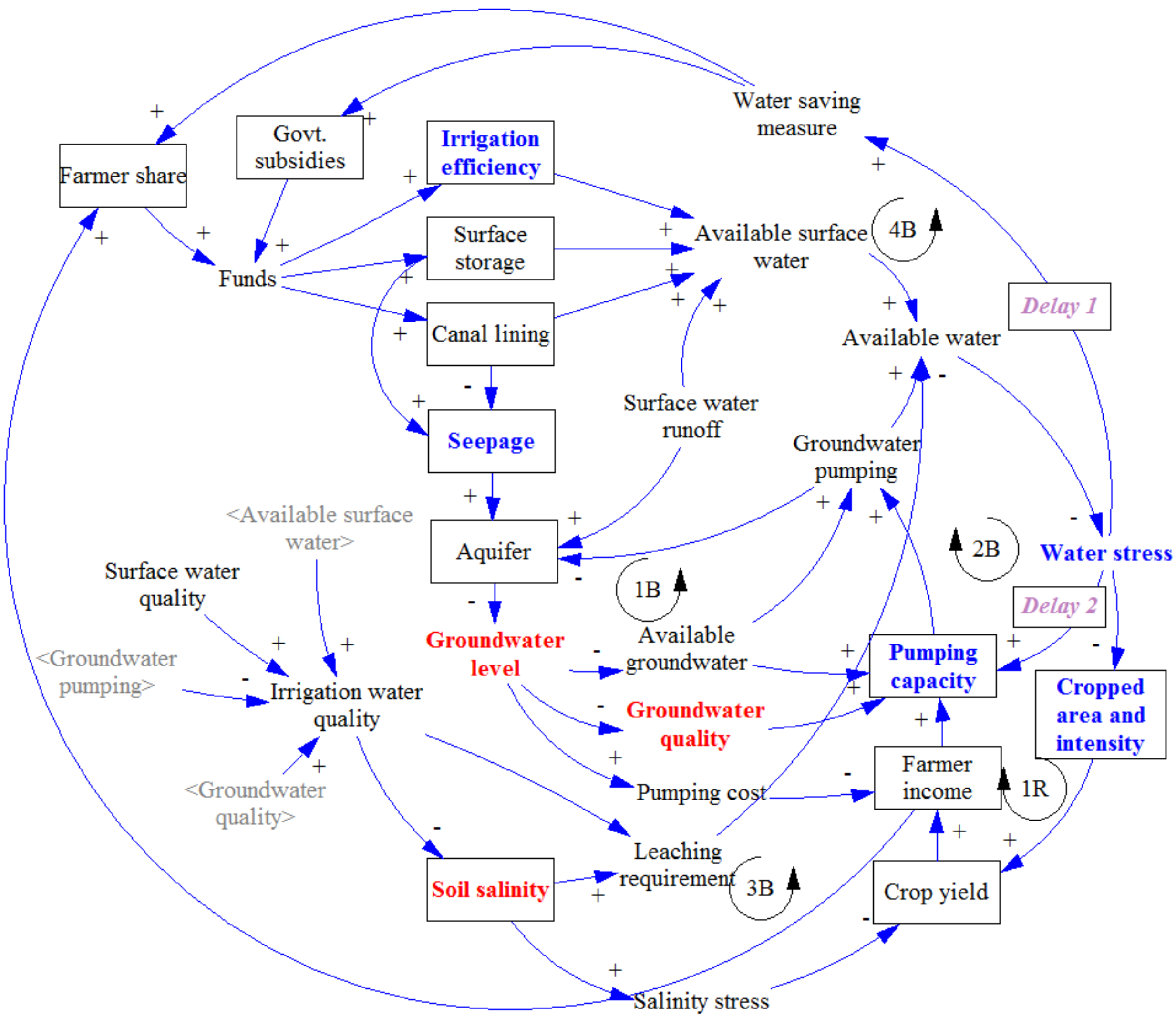


Figure 4.16. Key components of the integrated model with their relationships and feedback loops. Note: Red marked variables = SAHYSMOD interchanging variables; Blue marked variables = Vensim DSS interchanging variables; Purple marked variables = Delays; R = reinforcing and B = balancing behaviours.

The causal relationships were developed through active stakeholder participation, ensuring use of available knowledge about the real system [*Inam et al.* 2015]. The development of the model structure, based on the system dynamics literature (i.e. adopted sub-models of the existing model domain (see Table 4.2)), provides structure validation for the P-GBSDM.

4.6.1.3 Dimensional Consistency

The dimensional consistency test is important in checking each mathematical equation used in model formulation through unit consistency (i.e. left and right side units of an equation are consistent). Dimensional consistency ensures that each model equation corresponds to the real system. For example, the following equation in P-GBSDM distributes canal water supply in a polygon to crop a and crop b according to their cropped area and crop water requirement:

$$Canal\ supply_{a} = Canal\ contribution \times \frac{CWR_a \times CA_a}{(CWR_a \times CA_a) + (CWR_b \times CA_b)} \tag{4.37}$$

Where canal contribution is in m^3 season^{-1}, CWR_a and CWR_b are crop water requirements for crop *a* and crop *b*, respectively, in m season^{-1} and CA_a and CA_b are the cropped area under crop *a* and *b*, respectively, in m^2 season^{-1}. The dimensional analysis of the equation is as follows:

$$\text{m}^3\ \text{season}^{-1} = \text{m}^3\ \text{season}^{-1} \times \frac{(\frac{m}{season})\times m^2}{(\frac{m}{season})\times m^2} = \text{m}^3\ \text{season}^{-1}$$

Matching left and right hand side equation units indicate that an equation is dimensionally consistent. All interacting equations in P-GBSDM were subjected to dimensional consistency using the Vensim unit check built-in tool and were found to be correct.

4.6.1.4 Parameter Verification

The different parameter values assigned in P-GBSDM were sourced from the existing literature, as well as data published in reports from the Statistical Bureau of Pakistan. Spatial distribution of cropped areas, groundwater quality, soil salinity and soil classification were extracted through ArcGIS techniques (Kriging, zonal statistics, extraction by attribute, conversion) from maps produced by the International Water Management Institute (IWMI), Soil Monitoring Organization (SMO) and International Waterlogging and Salinity Research Institute (IWASRI). Due to space limitations, values, units and sources of some parameters are given in Table 4.3.

Table 4.3. P-GBSDM model parameter values from the literature

Parameter used	Value	Reference
Average life of tubewell (seasons)	20	*Agarwal* [2012]

Seepage rate ($m^3 sec^{-1}$ million m^{-2})	0.693 (Lined) 1.885 (Unlined)	*Skogerboe et al*. [1999]
Irrigation water quality (dS m^{-1})	0.55	*DLR* [2007]
Potential tubewell operating hours (hr)	235 (Winter) 355 (Summer)	*Qureshi et al*. [2003]
Threshold EC (dS m^{-1})	6.0 (Wheat) 2.8 (Sudan grass) 7.7 (Cotton) 1.5 (Berseem)	*Allen et al*. [2005]
B (% / dS m^{-1})	7.1 (Wheat) 4.3 (Sudan grass) 5.2 (Cotton) 5.7 (Berseem)	*Allen et al*. [2005]
K_y (Dimensionless)	1.05 (Wheat) 1.00 (Sudan grass) 0.85 (Cotton) 1.00 (Berseem)	*Allen et al*. [2005]
K_c (Dimensionless)	0.65 (Wheat) 0.70 (Suddan grass) 0.72 (Cotton) 0.85 (Berseem)	*Ullah et al*. [2001]
Irrigation efficiency (Fraction)	0.62 (Flood irrigation) 0.81 (Sprinkler irrigation) 0.90 (Drip irrigation)	*Shaikh et al*. [2015]
Lining cost (Rupees m^{-1}) in 1999 for channel carrying 8.5 $m^3 sec^{-1}$ discharge	3,725	*Skogerboe et al*. [1999]
Tubewell installation cost in terms of water table depth (Rupees m^{-1}) <6 m in 2003	56,796	*Qureshi et al*. [2003]
Tubewell operating cost (Rupees $year^{-1}$) in 2003	29,500	*Qureshi et al*. [2003]
Farmer loans (Rupees)	Lookup or table function	The Statistical Bureau of Pakistan, Economic Division, Year 1990-2010
Potential crop yield (Kg m^{-2})	Lookup or table function	Federal Bureau of Statistics, Agriculture Department, Year 1990-2010

Market prices (Rupees Kg^{-1})	Lookup or table function	Federal Bureau of Statistics, Economic Department, Year 1990-2010
Irrigation water quality EC standard (dS m^{-1})	Fit < 1.5 Marginally fit = 1.5-3.0 Unfit > 3.0	*Beg and Lone* [1992]

4.6.1.5 Extreme Conditions

Extreme condition tests evaluate model response by assigning extreme values to selected input variables and then check model-simulated behavior for the anticipated real conditions. P-GBSDM was subjected to extreme condition tests by setting extreme values of input variables such as canal diversions, sedimentation rate, groundwater extraction and surface storage. Then, model-generated behavior of endogenous variables, such as farm income, crop yield, groundwater depth and tubewell growth, was compared to the anticipated real behavior of the system. Figure 4.17 shows an example of the results of an extreme condition test simulated to evaluate the effect of wet and dry conditions on system behavior. Extreme conditions were achieved by setting no canal supplies (CS = 0) and very large supplies (CS = 10^{11} m^3 $season^{-1}$).

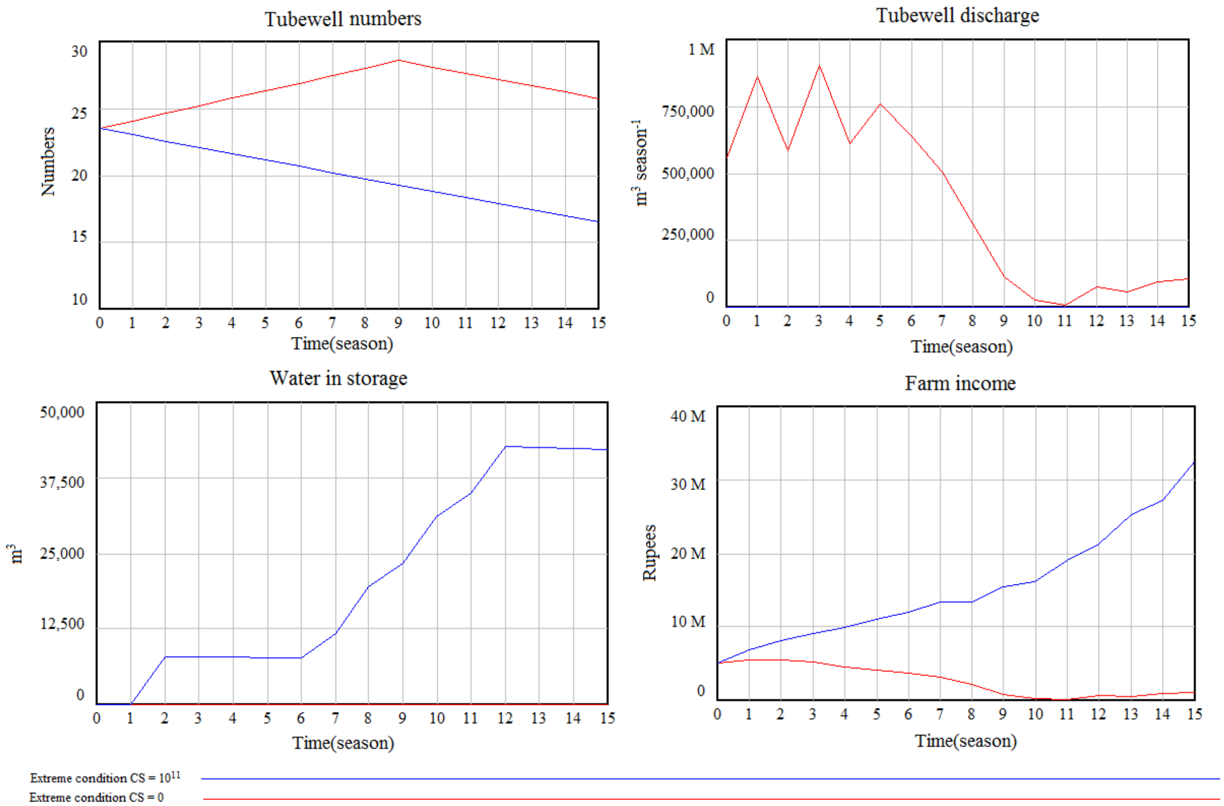


Figure 4.17. Simulated behavior of (a) tubewell numbers (b) tubewell discharge (c) water in surface storage (d) farm income under extreme conditions. Note: Red lines indicate low case behaviour and blue lines indicate high case behaviour.

For example, tubewell growth shows a steady decline under conditions of maximum canal supply while under conditions of no canal supply, tubewell growth first increases and then decreases. In the first case, assured canal water supplies reduce farmer dependency on groundwater resources, indicating no tubewells will be installed, and existing tubewells will depreciate at a steady rate. No canal supplies (CS = 0) indicate a high dependency on groundwater, which causes an increase in tubewell growth and results in more groundwater extracted from the aquifer. This growth is constrained by the available financial resources of farmers. Restricted growth limits groundwater supplies. No canal supplies (CS = 0) with limited groundwater supplies increase water stress. High water stress reduces crop yield and, therefore, farmer income. Shortages of financial resources seriously affects groundwater extraction, as well as tubewell growth. Based on numerous similar tests, the P-GBSDM generates behaviors comparable to anticipated real conditions, and therefore, it can be concluded that the model passes the extreme condition test, further confirming its validity.

4.6.2 Structurally-oriented Behavior Test

This test evaluates the behavioral validity of P-GBSDM (i.e. evaluating changes in model behavior with changes in input parameter values). The Vensim built-in Reality Check tool was used for structurally-oriented behavior tests and helps in model testing through the application of different test scenarios. Reality Check equations are quite different from the equations used in model quantification and need to be formulated by experts with the greatest knowledge of system behavior. For the current study, experts from IWMI, DLR, SMO and WAPDA were responsible for formulating Reality Check equations.

Reality Check temporarily replaces model equations with expressions assigned as "The condition" and then checks the model for anticipated consequences, assigned as "IMPLIES". If the anticipated behavior is not well-simulated, an error message is generated. For example, without any subsurface drainage, if there is no tubewell in the system and recharge and discharge equal zero, the water table should remain at a constant level. The Reality Check equation for this test can be written as:

$$\begin{aligned} &:The\ \ Condition\!:\text{Tubewell Nos } [polygon] = 0 \\ &\quad :AND\!:\ \text{Recharge to aquifer } [polygon] \ = \ 0 \\ &\quad :IMPLIES\!:\text{water table depth}_t[polygon] \\ &\quad = \ \text{water table depth}_{t-1}[polygon] \end{aligned} \tag{4.38}$$

This equation temporarily sets tubewell growth and aquifer recharge in each polygon to zero and compares groundwater level at time *t* with groundwater level at time *t*-1 within each model cell. In the case of any change in level in any polygon, an error message is generated. After completing this check, the equation resumes its original form. Reality Check provides the opportunity to test models after each update. Regardless of model size, a number of equations can be written and many simulations can be performed to check model behavior, thus helping to build confidence in the model. The following Reality Check tests, given with their equations, were carried out in order to build confidence in P-GBSDM simulations:

- Negative measures of tubewell growth, available water, cropped area, water in storage, water and salinity stress, crop water demand and farm income should never be observed under any simulation scenario (unrealistic negative behavior test).

$$\begin{aligned}
&: The\ \ Condition\text{: Canal supply at head } [Canal] = 0 \qquad (4.39)\\
&\qquad : AND\text{: Water requirement } [polygon] > 0\\
&\qquad : AND\text{: Policy RH} = 0\\
&: IMPLIES\text{: Tubewell Nos } [polygon] \geq 0\\
&\qquad : AND: Cropped\ \ area\ \ [polygon] \geq 0\\
&\qquad : AND: Storage\ \ supplies\ \ [polygon] = 0\\
&\qquad : AND: Water\ \ stress\ \ [polygon, crop] \geq 0\\
&\qquad : AND: Salinity\ \ stress\ \ [polygon, crop] \geq 0\\
&\qquad : AND: Farm\ \ income\ \ [polygon] \geq 0
\end{aligned}$$

- The sum of canal losses and farm canal supplies in polygons served by a particular canal should be equal to the volume of water diverted from the main canal (conservation of mass test).

$$\begin{aligned}
&: The\ \ Condition\text{: canal supply } [polygon] + \text{Canal seepage}[polygon] \qquad (4.40)\\
&\qquad + \text{supply losses } [polygon] \geq 0\\
&\qquad : IMPLIES\text{: Canal supply at head } [Canal]\\
&\qquad = \sum_{Polygon=1}^{i} (\text{canal supply } [polygon]\\
&\qquad + \text{Canal seepage}[polygon]\\
&\qquad + \text{supply losses } [polygon])
\end{aligned}$$

- Farm management measures such as canal lining, surface water storage and groundwater extraction are zero and irrigation efficiency is set to a minimum limit (0.60 as flood irrigation) if there is no farm income (constraint behavior limit test).

$$\begin{aligned}
&: The\ \ Condition\text{: Farm income } [polygon] = 0 \qquad (4.41)\\
&\qquad : IMPLIES\text{: Canal lining } [canal] = 0\\
&\qquad : AND: Tubewell\ \ discharge\ \ [polygon] = 0\\
&\qquad : AND: Constructed\ \ capacity\ \ [polygon] = 0\\
&\qquad : AND: Irrigation\ \ efficiency\ \ [polygon] = 0.6
\end{aligned}$$

- Supplies, seepage, evaporation, operation and maintenance expenditures and inflows to surface storage are zero if no surface storage capacities are available in the system (unrealistic positive behavior test).

$$\begin{aligned}
:\mathit{The\ \ Condition}\!:\mathrm{Policy\ \ RH} = 0 :\mathit{IMPLIES}\!:\ \ &\mathrm{SS\ \ supply}[\mathit{polygon}] \\
&= 0 : \mathrm{AND}\!: \mathrm{Seepage}[\mathit{polygon}] \\
&= 0\!: \mathrm{AND}\!: \mathrm{Evaporation}[\mathit{polygon}] = 0 \\
&: \mathrm{AND}\!: \mathrm{maintenance\ \ rate}[\mathit{polygon}] = 0 \\
&: \mathrm{AND}\!: \mathrm{Actual\ \ costs\ \ maintenance\ \ RH}[\mathit{polygon}] = 0 \\
&: \mathrm{AND}\!: \mathrm{inflow\ \ }[\mathit{polygon}] = 0
\end{aligned} \tag{4.42}$$

- Without any subsurface drainage, if there is no tubewell in the system and recharge and discharge from source or sink are zero, the water table level should remain constant (conservation of mass test).

$$\begin{aligned}
:\mathit{The\ \ Condition}\!:\mathrm{Tubewell\ \ Nos\ \ [polygon]} = 0 \\
&: \mathit{AND}\!:\ \mathrm{Recharge\ \ to\ \ aquifer\ \ [polygon]} \ = \ 0 \\
&: \mathit{IMPLIES}\!: \mathrm{water\ \ table\ \ depth}_t\mathrm{[polygon]} \\
&= \ \mathrm{water\ \ table\ \ depth}_{t-1}\mathrm{[polygon]}
\end{aligned} \tag{4.43}$$

In the above-mentioned test cases, each equation consists of a test input (the condition) coupled with an expected behavior or consequence (IMPLIES). Results of the above-mentioned tests are shown in Figure 4.18.

```
Starting testing of Constraint- Check when RWH is zero
Test inputs :
   Policy RH=0
 . . . testing - Check when RWH is zero[N1]
 . . . testing - Check when RWH is zero[N2]
 . . . testing - Check when RWH is zero[N3]
 . . . testing - Check when RWH is zero[N4]
 . . . testing - Check when RWH is zero[N5]
 . . . testing - Check when RWH is zero[N6]
 . . . testing - Check when RWH is zero[N7]
 . . . testing - Check when RWH is zero[N8]
 . . . testing - Check when RWH is zero[N9]
 . . . testing - Check when RWH is zero[N10]
……..
……..
……..
. . . testing - Farm income is zero[N206]
. . . testing - Farm income is zero[N207]
. . . testing - Farm income is zero[N208]
. . . testing - Farm income is zero[N209]
. . . testing - Farm income is zero[N210]
. . . testing - Farm income is zero[N211]
. . . testing - Farm income is zero[N212]
. . . testing - Farm income is zero[N213]
. . . testing - Farm income is zero[N214]
. . . testing - Farm income is zero[N215]
-------------

*****************
5 successes and 0 failures testing 5 Reality Check equations
The Reality Check Index as run is 8.28109e-010
Closeness score is 100.0% on 7305 measurements
```

Figure 4.18. Five Reality Checks with a summary of test results

The tests pass all five Reality Check scenarios with 7,305 measurements by performing tests on 215 polygons of P-GBSDM. The model structure was able to produce the anticipated real behaviour under tested scenarios, and therefore, it can be concluded with confidence that the formulated structures generate the right behaviours for the right reasons.

4.7 Model Strength and Future Work

The integrated P-GBSDM model framework is unique for several reasons. It identifies and meaningfully engages key stakeholders in the development and use of the model, thereby including stakeholders' perceptions and concerns in the model (regarding the causes of the problem, the consequences, feedback loops, and strategies to address the problem). The integrated model is based on a unique modeling framework that can successfully predict physical, environmental and socio-economic process interactions through feedback loops and through coupling a well-established agro, hydro and solute modeling package, SAHYSMOD (P component), with socio-economically feasible management solutions (that are accepted by local stakeholders) built into Vensim (GBSDM). The developed stock and flow structure enables the user to test different scenarios with considerations for aquifer sustainability, controlled tubewell growth and design of cropping patterns for maximum yield with economically feasible solutions and policies. The model can be used with different stakeholder groups (e.g. local farmers, experts, NGOs, government, etc.) to answer many "what if" questions. It can help decision-makers in making effective policy decisions with the participation of stakeholder groups. The integrated model can also help to initialize the process of meaningful stakeholder participation in model development and use, and it can also be used as a learning tool to create awareness between different stakeholder groups. Coupling both models (P and GBSDM) using a simple and flexible approach with commonly available software packages makes it accessible to users.

In future work, the authors will try to address soft data issues by coupling the model package with spatial variability software such as ArcGIS (ESRI) or ERDAS Imagine. Such integration will be helpful in quantifying the CLDs of stakeholders [*Inam et al.* 2015] from study area maps developed by experts. Another future goal will be to adapt the integrated model as a learning tool among stakeholders by creating policy maps and evaluating impacts on a watershed scale.

4.8 Conclusions

Appropriate aquifer and irrigation management are closely tied with soil salinity management solutions. Crop-water-soil systems are challenging to maintain in a sustainable manner, particularly in developing countries. Factors such as low farmer awareness, scarcity of irrigation water supplies, high cropping intensities and overexploitation of groundwater resources often hamper adaptation of effective management solutions. Involving stakeholders in strategy and policy formulation, decision making, and implementation can help formulate effective policies that consider local knowledge and stakeholders' perspectives. Conventional modeling techniques are often not feasible for stakeholder engagement, lack transparency, and are usually based on model-building without the consideration of stakeholders' perspectives and priorities. This paper discussed the development of a simple, flexible and easily adoptable integrated model that links SAHYSMOD, a physical agro-hydro salinity model, with a GBSDM built using Vensim DSS, an icon-based flexible modeling platform. The integrated P-GBSDM model is capable of simulating different aquifer and water management solutions with the consideration of physical and socio-economic interactions, and takes into account key stakeholder perspectives both in model development and use. The integrated model is developed using commonly available software tools, which can help increase its adoptability by experts, decision-makers and local stakeholders. With appropriate modifications, the proposed integrated modeling framework can be applied to other regions of the world facing similar problems. A companion paper will describe the model coupling procedures in more detail, and test the coupled model with different scenarios of agronomic and water management options in sub-watershed regions of the Rechna Doab basin, Pakistan.

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Appendix A

1. Auxiliary variables

Variable name	Unit	Equation
Actual capacity of tubewell	m^3 $season^{-1}$	Actual capacity of TW[Polygon] = Tubewell Nos[Polygon]*Capacity per tubewell*Actual operating hours[Polygon]
Actual costs of maintenance rainwater harvesting	Rs $season^{-1}$	Actual costs maintenance RH[Polygon] = Cost of maintenance*maintenance rate[Polygon]
Actual improvement cost	Rs $season^{-1}$	Actual improvement cost[Polygon] = No of units[Polygon]*Cost of installation
Actual lining cost	Rs $season^{-1}$	Actual lining cost[canal] = cost of lining*Lining rate[canal]
Actual maintenance rate	Dimensionless	Actual maintenance rate[Polygon] = IF THEN ELSE(maintenance cost[Polygon]=0, 1 , IF THEN ELSE(Potential investment[Polygon]>maintenance cost[Polygon], 1 , Potential investment[Polygon]/maintenance cost[Polygon]))
Actual operating cost	Rs $season^{-1}$	Actual operating cost[Polygon] = Tubewell Nos[Polygon]*Operating cost per hr*Actual operating hours[Polygon]
Actual operating hours	hrs $season^{-1}$ nos^{-1}	Actual operating hours[Polygon] = Max(MIN(Potential investment[Polygon]/(Operating cost per hr*Tubewell Nos[Polygon]),potential operating hours),0)
Actual RWH Costs	Rs $season^{-1}$	Actual RWH Costs[Polygon] = Cost of pond*Construction rate[Polygon]
Annual maintenance cost	Rs $season^{-1}$ nos^{-1}	annual maintenance cost = maintenance cost year 2003*maintenance factor*(IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0))
Available canal supplies contributions to SS	m^3 $season^{-1}$	Available canalsupplies contributions to SS[Polygon] = IF THEN ELSE(water in storage[Polygon]<Available capacity[Polygon], MIN(canal supply in polygon[Polygon]-Canal contributions [Polygon],(Available capacity[Polygon]-water in storage[Polygon])/TIME STEP) , 0)
Available capacity	m^3	Available capacity[Polygon] = Max(Constructed capacity[Polygon]-Silted capacity[Polygon],0)
Available runoff contribution to SS	m^3 $season^{-1}$	Available runoff contribution to SS[Polygon] = IF THEN ELSE(water in storage[Polygon]<Available capacity[Polygon], MIN(Runoff[Polygon], (Available capacity[Polygon]-water in storage[Polygon])/TIME STEP) , 0)
Canal contributions	m^3 $season^{-1}$	Canal contributions[Polygon] = IF THEN ELSE(Water requirment[Polygon]>Rainfall contributions, MIN(Water requirment[Polygon]-Rainfall contributions,canal supply in polygon[Polygon]) , 0)
Canal decay rate	m $season^{-1}$	canal decay rate[canal] = IF THEN ELSE(Time<Average canal decay time , Canal lining zero time stock[canal]/Average canal decay time , delay rate CL[canal])
Canal evaporation	m^3 $season^{-1}$	canal evaporation[canal] = MIN(Canal supply at head[canal]*Ep,Canal supply at head[canal])
Canal seepage	m^2 $season^{-1}$	Canal seepage[canal] = 4.27*(Canal supply at head[canal])^0.658
Canal seepage per polygon	m^3 $season^{-1}$	Canal seepage per polygon[Polygon] = SUM(Seepage distribution[Polygon,canal!])
Canal supply in polygon	m^3 $season^{-1}$	canal supply in polygon[Polygon] = SUM(Distributed supply[Polygon,canal!])
Canal supply per crop	m^3 $season^{-1}$	canal supply per crop[Polygon,c1] = Canal contributions[Polygon]*((crop seasonal water requirement[c1]*Crop area[Polygon,c1])/((crop seasonal water requirement[c1]*Crop area[Polygon,c1])+(crop seasonal water requirement[c2]*Crop area[Polygon,c2])))*IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0)
Capacity Increase	m^3	Capacity Increase[Polygon] = Capcacity Lookup(Year)*Total rainwater harvesting capacity
Canal lining share	Rs $season^{-1}$	CL share[canal] = Farmer share[canal]/Nos of served polygon[canal]
Construction Percentage	Dimensionless	Construction Percentage[Polygon] = Constructed capacity[Polygon]/Total rainwater harvesting capacity

Variable name	Unit	Equation
Construction rate	m^3 $season^{-1}$	Construction rate[Polygon] = IF THEN ELSE(RWH cost per season[Polygon]<=Potential investment[Polygon],IF THEN ELSE(Constructed capacity[Polygon]<Total rainwater harvesting capacity, Incremental Increase[Polygon]/TIME STEP *Policy RH, 0),0)
Consumption	m^3 $season^{-1}$	Consumption[Polygon] = MIN(Canal contributions[Polygon]+Rainfall contributions+SS supply[Polygon]+Tubewell discharge[Polygon],Water requirment[Polygon])
Cost factor	Dimensionless	Cost factor = Lookup function(Year)
Cost of installation	Rs $unit^{-1}$	Cost of installation = Installation cost factor*Installation cost 2003
Cost of installation per season	Rs $season^{-1}$	cost of installation per season[Polygon] = units per season[Polygon]/TIME STEP*Cost of installation*0.25
Cost of lining	Rs m^{-1}	cost of lining = Lining cost factor*Lining cost year 2003
Cost of maintenance	Rs m^{-3}	Cost of maintenance = Maintenance cost factor*Maintence cost yesr 2003
Cost of pond	Rs m^{-3}	Cost of pond = Pond cost factor*Pond cost year 2003
Costs for potential tubewell installation	Rs $season^{-1}$	Costs for potential tubewell installation[Polygon] = Desired Additional TW installed[Polygon]*Costs per tubwell[Polygon]
Costs per tubewell	Rs nos^{-1}	Costs per tubwell[Polygon] = Cost factor*Installation cost[Polygon]
Crop area	m^2	Crop area[Polygon,crops] = Area fraction[Polygon,crops]*Area
Crop income	Rs $season^{-1}$	Croped income[Polygon,kc1,c1] = Crop area[Polygon,c1]*CY[Polygon,kc1,c1]*Market rate[c1]
CY	Kg m^{-2} $season^{-1}$	CY[Polygon,kc1,c1] = CY max[c1]*Salinity stress[Polygon,c1]*Water stress[Polygon,kc1,c1]
Deep percolated	m^3 $season^{-1}$	Deep percolated[Polygon] = Uneffective rainfall[Polygon]*Cp rainfall
Desired additional TW installed	nos $season^{-1}$	Desired Additional TW installed[Polygon] = IF THEN ELSE(Required capacity[Polygon]<=0, 0 , Tubewell installed per season[Polygon])
Distributed supply	m^3 $season^{-1}$	Distributed supply[Polygon,canal] = IF THEN ELSE(Distribution switch[canal]=1, IF THEN ELSE(Field location[Polygon,canal]<0.33, Supply after losses[canal]*Distribution factor[Polygon,canal]/Canal division[canal,Head], IF THEN ELSE(Field location[Polygon,canal]<0.66:AND:Field location[Polygon,canal]>0.33, Supply after losses[canal]*Distribution factor[Polygon ,canal]/Canal division[canal,Middle] , Supply after losses[canal]*Distribution factor[Polygon,canal]/Canal division[canal,Tail])), Equally distributed[canal]*Nos of served polygon[canal]*(1/Nos of served polygon[canal]))*Active[Polygon,canal]
Distribution factor	Dimensionless	Distribution factor[Polygon,canal] = Distribution lookup(Field location[Polygon,canal])
ECicw	dS m^{-1}	ECicw[Polygon] = IF THEN ELSE(Viw[Polygon]=0:AND:ECdw[Polygon]>7.46, 0.99 , (Viw[Polygon]*Eciw[Polygon]+Vdw[Polygon]*ECdw[Polygon])/(Viw[Polygon]+Vdw[Polygon]))
Equal distribution of seepage	m^3 $season^{-1}$	Equal distribution of seepage[canal] = Net canal seepage[canal]/(No of polygon over canal[canal])
Equally distributed	m^3 $season^{-1}$	Equally distributed[canal] = Supply after losses[canal]/(Nos of served polygon[canal])
ETc Rate	m^3 $season^{-1}$	ETc Rate[Polygon,kc2,c2] = Kc[kc2]*Reference ET[Polygon]*Crop area[Polygon,c2]*(IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0))
Evaporation1	m^3 $season^{-1}$	Evaporation1[Polygon] = MIN(Width*Width*Seasonal evaporation,water in storage[Polygon]/TIME STEP)
Expenditure	Rs $season^{-1}$	Expenditure[Polygon] = Actual operating cost[Polygon]+Costs for potential tubewell installation[Polygon]+Farmer irrigation improvement share[Polygon]+Actual costs maintenance RH[Polygon]+Farmer water harvesting share[Polygon]+Lining expenditure[Polygon]+maintenance cost[Polygon]+Payments[Polygon]
Farmer irrigation improvement share	Rs $season^{-1}$	Farmer irrigation improvement share[Polygon] = Irrigation improvement investment[Polygon]*0.25
Farmer share	Rs $season^{-1}$	Farmer share[canal] = Investment[canal]*0.25
Farmer water harvesting share	Rs $season^{-1}$	Farmer water harvesting share[Polygon] = Investment RH[Polygon]*0.25

Variable name	Unit	Equation
Field location	Dimensionless	Field location[Polygon,canal] = IF THEN ELSE (Active[Polygon,canal]=1 , RD[Polygon]/Channel length[canal] , 0)
Fuel cost	Rs $liters^{-1}$	Fuel cost = Fuel price in year 2003*Inflation factor
Governament irrigation improvement share	Rs $season^{-1}$	Governament irrigation improvement share[Polygon] = Irrigation improvement investment[Polygon]*0.75
Govt. share	Rs $season^{-1}$	"Govt. share"[canal] = Investment[canal]*0.75
Govt. water harvesting share	Rs $season^{-1}$	"Govt. water harvesting share"[Polygon] = Investment RH[Polygon]*0.75
Gw	m $season^{-1}$	Gw[Polygon] = Tubewell discharge[Polygon]/Area
Ia	m $season^{-1}$	Ia[Polygon,crops] = Surface supply per crop[Polygon,crops]/Area
Improvement rate	$Season^{-1}$	Improvement rate[Polygon] = IF THEN ELSE(cost of installation per season[Polygon]<=Potential investment[Polygon],MIN((Problem perception of irrigation efficiency[Polygon]*Irrigation Efficiency improvement[Polygon]/TIME STEP*Policy Irrigation improvement), (-Irrigation efficiency[Polygon]+Efficiency goal)/TIME STEP),0)
Income	Rs $season^{-1}$	Income[Polygon] = Croped income[Polygon,kc1,c1]+Croped income[Polygon,kc2,c2]+Croped income[Polygon,kc3,c3]+Croped income[Polygon,kc4,c4]+"Govt. loan"
Incremental increase	m^3	Incremental Increase[Polygon] = Max(Capacity Increase[Polygon]-Constructed capacity[Polygon],0)
Incremental length lined	m	Incremental Length lined[canal] = lookup canal lined[canal](Year)*Total length[canal]
Inflation factor	Dimensionless	Inflation factor = diesel cost lookup(Year)
inflow	m^3 $season^{-1}$	inflow[Polygon] = Available canalsupplies contributions to SS[Polygon]+Available runoff contribution to SS[Polygon]
Installation cost	Rs nos^{-1}	Installation cost[Polygon] = Standard cost * Cost vs depth lookup(watertable depth[Polygon] / Standard depth)
Installation cost factor	Dimensionless	Installation cost factor = Lookup function(Year)
Investment	Rs $season^{-1}$	Investment[canal] = Actual lining cost[canal]
Investment RH	Rs $season^{-1}$	Investment RH[Polygon] = Actual RWH Costs[Polygon]
Irrigation efficiency improvement	Dimensionless	Irrigation Efficiency improvement[Polygon] = Efficiency improvement lookup[Polygon](Year)
Irrigation improvement investment	Rs $season^{-1}$	Irrigation improvement investment[Polygon] = Actual improvement cost[Polygon]
Lc	m $season^{-1}$	Lc[Polygon] = Recharge to aquifer[Polygon]/Area
leaching fraction	m^3 $season^{-1}$	leaching fraction[Polygon,kc1,c1] = ETc Rate[Polygon,kc1,c1]/(1-LR[Polygon,c1])
lined percentage	Dimensionless	lined percentage[canal] = Canal lining[canal]/Total length[canal]
Lining cost factor	Dimensionless	Lining cost factor = Lookup function(Year)
Lining cost per season	Rs $season^{-1}$	lining cost per season[canal] = (Incremental Length lined[canal]/TIME STEP)*cost of lining*0.25
Lining expenditure	Rs $season^{-1}$	Lining expenditure[Polygon] = SUM(Per Polygon CL share[Polygon,canal!])
Lining rate	m $season^{-1}$	Lining rate[canal] = IF THEN ELSE(lining cost per season[canal]<=Potential investment per canal[canal],MIN(Problem perception state of canals[canal]*Incremental Length lined[canal]/TIME STEP*Policy Canal lining[canal],(Total length [canal]-Canal lining[canal])/TIME STEP),0)
Loan	Rs $season^{-1}$	Loan[Polygon] = (Interest rate*Debt[Polygon]+"Govt. loan")*(IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0))
LR	Dimensionless	LR[Polygon,c1] = ECicw[Polygon]/(5*ECe[c1]-ECicw[Polygon])
Maintenance cost	Rs $season^{-1}$	maintenance cost[Polygon] = annual maintence cost*Tubewell Nos[Polygon]
Maintenance cost factor	Dimensionless	Maintenance cost factor = Lookup function(Year)
Maintenance rate	m^3 $season^{-1}$	maintenance rate[Polygon] = Silted capacity[Polygon]/TIME STEP*Siltation perception Farmers[Polygon]

Variable name	**Unit**	**Equation**
Maintenance factor	Dimensionless	Maintence factor = Lookup function(Year)
Max Capacity tubewells	m^3 $season^{-1}$	Max Capacity Tubewells[Polygon] = Tubewell Nos[Polygon]*Capacity per tubewell*potential operating hours
Net canal seepage	m^3 $season^{-1}$	Net canal seepage[canal] = Canal seepage[canal]*(length in miles[canal]-(lined percentage[canal]*length in miles[canal]*(1-percentage losses lined)))
No of units	unit $season^{-1}$	No of units[Polygon] = Improvement rate[Polygon]/Efficiency increse per unit
Operating cost per hr	Rs hrs^{-1}	Operating cost per hr = Dieseal consumption*Fuel cost
Payments	Rs $season^{-1}$	Payments[Polygon] = Percent of total income/100*Income[Polygon]
Per Polygon CL share	Rs $season^{-1}$	Per Polygon CL share[Polygon,canal] = CL share[canal]*Polygonal factor[Polygon,canal]
Pond cost factor	Dimensionless	Pond cost factor = Lookup function(Year)
Potential investment	Rs $season^{-1}$	Potential investment[Polygon] = Farm income[Polygon]/TIME STEP*0.2
Potential investment per canal	Rs $season^{-1}$	Potential investment per canal[canal] = SUM(Potential investment polygons on canal[canal,Polygon!])
Potential investment polygons on canal	Rs $season^{-1}$	Potential investment polygons on canal[canal,Polygon] = Potential investment[Polygon]*Polygonal factor[Polygon,canal]
Potential operating hours	hrs $season^{-1}$ nos^{-1}	potential operating hours = IF THEN ELSE(MODULO(Time, 2)=0, 235 , 355)
Potential operational cost	Rs $season^{-1}$	Potential operational cost[Polygon] = Tubewell Nos[Polygon]*potential operating hours*Fuel cost*Dieseal consumption
Problem perception of irrigation efficiency	Dimensionless	Problem perception of irrigation efficiency[Polygon] = Irrigation efficiency perception lookup(Irrigation efficiency[Polygon]/Efficiency goal)
Problem perception state of canals	Dimensionless	Problem perception state of canals[canal] = Perception lookup(Canal lining[canal]/Total length[canal])
Rainfall contributions	m^3 $season^{-1}$	Rainfall contributions = Effective rainfall*Area
Rainfall volume	m^3 $season^{-1}$	Rainfall volume = Rainfall*Area
Recharge to aquifer	m^3 $season^{-1}$	Recharge to aquifer[Polygon] = Canal seepage per polygon[Polygon]*Cp+Recharge to aquifer rainfall[Polygon]
Recharge to aquifer rainfall	m^3 $season^{-1}$	Recharge to aquifer rainfall[Polygon] = Deep percolated[Polygon]
Required capacity	m^3 $season^{-1}$	Required capacity[Polygon] = IF THEN ELSE(Max Capacity Tubewells[Polygon]>Required flow rate[Polygon], 0 , -Max Capacity Tubewells[Polygon]+Required flow rate[Polygon])
Required flow rate	m^3 $season^{-1}$	Required flow rate[Polygon] = Water requirment[Polygon]-Surface supply[Polygon]-SS supply[Polygon]
Runoff	m^3 $season^{-1}$	Runoff[Polygon] = Uneffective rainfall[Polygon]-Deep percolated[Polygon]
Runoff supply per crop	m^3 $season^{-1}$	Runoff supply per crop[Polygon,c1] = (Rainfall contributions/Area)*Crop area[Polygon,c1]*IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0)
RWH cost per season	Rs $season^{-1}$	RWH cost per season[Polygon] = (Incremental Increase[Polygon]/TIME STEP)*Cost of pond*0.25
Salinity stress	fraction	Salinity stress [Polygon,c1] = Max(1-((IF THEN ELSE(Soil salinity[Polygon,c1]<ECthreshold[c1], ECthreshold[c1] , Soil salinity[Polygon,c1])-ECthreshold[c1])*b[c1]/100),0)
SAVEPER	season	SAVEPER = TIME STEP
Seepage distribution	m^3 $season^{-1}$	Seepage distribution[Polygon,canal] = IF THEN ELSE(Distribution switch[canal]=1, IF THEN ELSE(Seepage field location[Polygon,canal]<0.33, Net canal seepage[canal]*Seepage distribution factor[Polygon,canal]/Canal division[canal,Head], IF THEN ELSE(Seepage field location[Polygon,canal]<0.66:AND:Seepage field location[Polygon,canal]>0.33, Net canal seepage[canal]*Seepage distribution factor[Polygon,canal]/Canal division[canal,Middle] , Net canal seepage[canal]*Seepage distribution factor[Polygon,canal]/Canal division[canal,Tail])), Equal distribution of seepage[canal])*active seep[Polygon,canal]

Variable name	Unit	Equation
Seepage distribution factor	Dimensionless	Seepage distribution factor[Polygon,canal] = Polygon lookup(Seepage field location[Polygon,canal])
Seepage field location	Dimensionless	Seepage field location[Polygon,canal] = IF THEN ELSE (active seep[Polygon,canal]=1 , Polygon RD[Polygon]/Channel length[canal] , 0)
Seepage1	m^3 season^{-1}	Seepage1[Polygon] = MIN(SF*(Width*Width+(4*water in storage[Polygon]/Width)),water in storage[Polygon]/TIME STEP)
Siltation perception Farmers	Dimensionless	Siltation perception Farmers[Polygon] = IF THEN ELSE(Constructed capacity[Polygon]=0, 0 , Siltation perception lookup(Silted capacity[Polygon]/Constructed capacity[Polygon]))
Siltation rate	m^3 season^{-1}	Siltation rate[Polygon] = IF THEN ELSE(Available capacity[Polygon]>0, Sediment doposition rate*tanks per cell , 0)
SS supply	m^3 season^{-1}	SS supply[Polygon] = IF THEN ELSE(Water requirment[Polygon]>(Total canal supplies[Polygon]+Rainfall contributions),MIN((Water requirment[Polygon]-Rainfall contributions-Total canal supplies[Polygon]) , (water in storage[Polygon]/TIME STEP-Evaporation1[Polygon]-Seepage1[Polygon])),0)
SS supply per crop	m^3 season^{-1}	SS supply per crop[Polygon,c1] = (SS supply[Polygon])*((crop seasonal water requirement[c1]*Crop area[Polygon,c1])/((crop seasonal water requirement[c1]*Crop area[Polygon,c1])+(crop seasonal water requirement[c2]*Crop area[Polygon,c2])))*IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0)
Supply	m^3 season^{-1}	Supply[Polygon] = Canal contributions[Polygon]+Rainfall contributions+Tubewell discharge[Polygon]
Supply after losses	m^3 season^{-1}	Supply after losses[canal] = Max(Canal supply at head[canal]-Net canal seepage[canal]-canal evaporation[canal],0)
Surface supply	m^3 season^{-1}	Surface supply[Polygon] = Canal contributions[Polygon]+Rainfall contributions
Surface supply per crop	m^3 season^{-1}	Surface supply per crop[Polygon,crops] = SS supply per crop[Polygon,crops]+Runoff supply per crop[Polygon,crops] + canal supply per crop[Polygon,crops]
switch	Dimensionless	switch[Polygon] = IF THEN ELSE(Irrigation efficiency[Polygon]<=Minimum efficiency, 0 , 1)
Total canal supplies	m^3 season^{-1}	Total canal supplies[Polygon] = SUM(canal supply per crop[Polygon,crops!])
Total rainwater harvesting capacity	m^3	Total rainwater harvesting capacity = Height*Length*Tank width*tanks per cell
Total supply per crop	m^3 season^{-1}	Total supply per crop[Polygon,crops] = TW supply per crop[Polygon,crops]+Surface supply per crop[Polygon,crops]
Tubewell decay	nos season^{-1}	Tubewell decay[Polygon] = Tubewell Nos[Polygon]/Average TW life
Tubewell discharge	m^3 season^{-1}	Tubewell discharge[Polygon] = Max(MIN(Required flow rate[Polygon],Actual capacity of TW[Polygon]),0)
Tubewell growth	nos season^{-1}	Tubewell growth[Polygon] = IF THEN ELSE(Tubewell Nos[Polygon] < maximum allowable number of tubewells :AND: ECdw[Polygon] < Threshold EC for tubewell installation, IF THEN ELSE(Costs for potential tubewell installation[Polygon]<=Potential investment[Polygon],Desired Additional TW installed[Polygon], 0) , 0)
Tubewell installed per season	nos season^{-1}	Tubewell installed per season[Polygon] = 0.75+Tubewell decay[Polygon]*Factor
TW supply per crop	m^3 season^{-1}	TW supply per crop[Polygon,c1] = (Tubewell discharge[Polygon])*((crop seasonal water requirement[c1]*Crop area[Polygon,c1])/((crop seasonal water requirement[c1]*Crop area[Polygon,c1])+(crop seasonal water requirement[c2]*Crop area[Polygon,c2])))*IF THEN ELSE(MODULO(Time, 2)=0, 1 , 0)
Uneffective rainfall	m^3 season^{-1}	Uneffective rainfall[Polygon] = Rainfall volume-Rainfall contributions
units per season	Unit	units per season[Polygon] = Irrigation Efficiency improvement[Polygon]/Efficiency increse per unit
Unused	m^3 season^{-1}	Unused[Polygon] = Supply[Polygon]+SS supply[Polygon]-Consumption[Polygon]
Vdw	m^3 season^{-1}	Vdw[Polygon] = Tubewell discharge[Polygon]
Viw	m^3 season^{-1}	Viw[Polygon] = canal supply in polygon[Polygon]
Water requirment	m^3 season^{-1}	Water requirment[Polygon] = (ETc Rate[Polygon,kc1,c1]+ETc Rate[Polygon,kc2,c2]+ETc Rate[Polygon,kc3,c3]+ETc Rate[Polygon,kc4,c4])/Irrigation efficiency[Polygon]
Water stress	Dimensionless	Water stress[Polygon,kc1,c1] = Max(IF THEN ELSE(ETc Rate[Polygon,kc1,c1]=0, 0 , 1-((Ky[c1])*(1-(IF THEN ELSE(Total supply per crop[Polygon,c1]> ETc Rate[Polygon,kc1,c1], ETc Rate[Polygon,kc1,c1] , Total supply per crop[Polygon,c1])/ETc Rate[Polygon,kc1,c1])))) , 0)
Year	Dimensionless	Year= RAMP(1 , 0 , 96)/2+Starting year

2. Stocks\level variables

Variable name	Unit	Equation
AW	m^3	AW[Polygon]= INTEG (SS supply[Polygon]+Supply[Polygon]-Consumption[Polygon]-Unused[Polygon], AW zero time stock[Polygon])
Canal lining	M	Canal lining[canal]= INTEG (Lining rate[canal]-canal decay rate[canal], Canal lining zero time stock[canal])
Constructed capacity	m^3	Constructed capacity[Polygon]= INTEG (Construction rate[Polygon], constructed capacity zero time stock[Polygon])
Debt	Rs	Debt[Polygon]= INTEG (Loan[Polygon]-Payments[Polygon], Debt zero time stock[Polygon])
Farm income	Rs	Farm income[Polygon]= INTEG (Income[Polygon]-Expenditure[Polygon], Farm income zero time stock[Polygon])
Irrigation efficiency	Dimensionless	Irrigation efficiency[Polygon]= INTEG (Improvement rate[Polygon]-Structure decay rate[Polygon], Irrigation efficiency zero time stock[Polygon])
Silted capacity	m^3	Silted capacity[Polygon]= INTEG (Siltation rate[Polygon]-maintenance rate[Polygon], silted capacity zero time stock[Polygon])
Total water requirments	m^3	Total water requirments[Polygon,kc1,c1]= INTEG (leaching fraction[Polygon,kc1,c1], Total water requirments zero time stock[Polygon])
Tubewell Nos	Nos	Tubewell Nos[Polygon]= INTEG (Tubewell growth[Polygon]-Tubewell decay[Polygon], Tubewell number at zero time[Polygon])
water in storage	m^3	water in storage[Polygon]= INTEG (inflow[Polygon]-Evaporation1[Polygon]-Seepage1[Polygon]-SS supply[Polygon], Water in storage zero time stock[Polygon])

3. Data variables

Variable name	Unit	Equation
Area fraction	Dimensionless	Area fraction[Polygon,c1]:INTERPOLATE:: = GET XLS DATA('?test', 'AF' , 'A' , 'B3')
Canal supply at head	m^3 $season^{-1}$	Canal supply at head[canal]:INTERPOLATE:: = GET XLS DATA('?test', 'Canals supply' , 'b' , 'c4')
CY max	Kg m^{-2} $season^{-1}$	CY max[crops]:INTERPOLATE:: = GET XLS DATA('?test', 'Crop_Yield' , 'b' , 'c2')
ECdw	dS m^{-1}	ECdw[Polygon]: = GET XLS DATA('?test', 'ECdw' , 'A' , 'B3')
Effective rainfall	m $season^{-1}$	Effective rainfall: = GET XLS DATA('?test' , 'rainfall', 'a', 'c2')
"Govt. loan"	Rs $season^{-1}$	"Govt. loan":INTERPOLATE:: = GET XLS DATA('?test', 'Loan' , 'e' , 'F2')
Interest rate	fraction $season^{-1}$	Interest rate:INTERPOLATE:: = GET XLS DATA('?test', 'Loan' , 'e' , 'G2')
Market rate	Rs Kg^{-1}	Market rate[crops]:INTERPOLATE:: = GET XLS DATA('?test', 'Market_Rate' , 'h' , 'I2')
Rainfall	m $season^{-1}$	Rainfall: = GET XLS DATA('?test' , 'rainfall', 'a', 'b2')
Reference ET	m $season^{-1}$	Reference ET[Polygon]:INTERPOLATE:: = GET XLS DATA('?test', 'ETref' , 'b' , 'c3')
Seasonal evaporation	m $season^{-1}$	Seasonal evaporation: = GET XLS DATA('?test' , 'SEvapo', 'a', 'b2')
Soil salinity	dS m^{-1}	Soil salinity[Polygon,c1]:INTERPOLATE:: = GET XLS DATA('?test', 'SS' , 'A' , 'B3')
watertable depth	m	watertable depth[Polygon]: = GET XLS DATA('?test', 'WTD' , 'A' , 'B3')

4. Lookup variables

Variable name	Unit	Equation
Capacity Lookup	Dimensionless	Capacity Lookup = GET XLS LOOKUPS('?test', 'Capacity increase' , 'a' , 'b2')
Cost vs depth lookup	Dimensionless	Cost vs depth lookup ([(0,0)-(5,6)],(0,1),(1,1),(1.01,1.47),(2,1.47),(2.01,2.8),(3,2.8),(3.01,4.9),(4,4.9),(4.01,5.97),(5,5.97))
diesel cost lookup	Dimensionless	Diesel cost lookup = GET XLS LOOKUPS('?test', 'Diesel_cost' , 'a', 'b2')
Distribution lookup	Dimensionless	Distribution lookup ([(0,0)-(1,1)],(0,0),(0.0015,0.45),(0.329,0.45),(0.33,0.35),(0.659,0.35),(0.66,0.2),(0.999,0.2),(1,0.2))
Efficiency improvement lookup	Dimensionless	Efficiency improvement lookup[Polygon] = GET XLS LOOKUPS('?test', 'Irreff lookup' , 'a', 'b2')
Irrigation efficiency perception lookup	Dimensionless	Irrigation efficiency perception lookup ([(0,0)-(1,1)],(0.6,1),(0.65,1),(0.7,1),(0.75,1),(0.85,0.6),(0.9,0.5),(1,0.01))
lookup canal lined	Dimensionless	lookup canal lined[canal] = GET XLS LOOKUPS ('?test', 'Canal lining policy' , 'a', 'b2')
Lookup function	Dimensionless	Lookup function = GET XLS LOOKUPS('?test', 'Inflation' , 'a', 'b2')
Perception lookup	Dimensionless	Perception lookup ([(0,0)-(1,1)],(0,1),(0.2,1),(0.5,1),(0.63,1),(0.688,0.98),(0.792,0.93),(0.89,0.82),(0.9,0.72),(0.94,0.64),(0.96,0.53),(1,0))
Polygon lookup	Dimensionless	Polygon lookup ([(0,0)-(1,1)],(0,0),(0.0015,0.45),(0.329,0.45),(0.33,0.35),(0.659,0.35),(0.66,0.2),(0.999,0.2),(1,0.2))
Siltation perception lookup	Dimensionless	Siltation perception lookup ([(0,0)-(1,1)],(0,0),(0.2,0),(0.5,0),(0.63,0.2),(0.688,0.3),(0.792,0.5),(0.89,0.9),(0.9,0.9),(0.94,1),(0.96,1),(1,1))

5. Constants

Variable name	Unit	Equation
Active	Dimensionless	Active[Polygon,canal] = GET XLS CONSTANTS('?test' , 'Active' , 'b2')
Active seep	Dimensionless	active seep[Polygon,canal] = GET XLS CONSTANTS('?test' , 'Active' , 'b2')
Area	m^{-2}	4.41e+006
Average canal decay time	season	30
Average TW life	season	20
AW zero time stock	m^3	AW zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'AWS' , 'b2*')
b	m fraction dS^{-1}	b[crops] = 7.1, 4.3, 5.2, 12
Canal division	Dimensionless	Canal division[canal,position] = GET XLS CONSTANTS('?test' , 'Position' , 'b2')
Canal lining zero time stock	m	Canal lining zero time stock[canal] = GET XLS CONSTANTS('?test', 'CLS' , 'b2*')
Capacity per tubewell	m^3 hrs^{-1}	100.8
Channel length	m	Channel length[canal] = GET XLS CONSTANTS('?test', 'CL' , 'b2*')
constructed capacity zero time stock	m^3	constructed capacity zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'CC' , 'b2*')
Cp	Dimensionless	0.2
Cp rainfall	Dimensionless	0.2
crop seasonal water requirement	mm $season^{-1}$	crop seasonal water requirement[crops] = GET XLS CONSTANTS('?test', 'CWR' , 'B2*')
Debt zero time stock	Rs	Debt zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'DEB' , 'b2*')
Dieseal consumption	liters hrs^{-1}	2.5
Distribution switch	Dimensionless	Distribution switch[canal] = 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
ECe	dS m^{-1}	ECe[crops] = GET XLS CONSTANTS('?test' , 'ECe' , 'b2*')
Eciw	dS m^{-1}	Eciw[Polygon] = 0.54
ECthreshold	dS m^{-1}	ECthreshold[crops] = 6, 2.8, 7.7, 3
Efficiency goal	Dimensionless	0.85
Efficiency increse per unit	$Unit^{-1}$	0.05
Ep	Dimensionless	0.1
Factor	Dimensionless	0.6
Farm income zero time stock	Rs	Farm income zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'FIC' , 'b2*')
FINAL TIME	season	40
Fuel price in year 2003	Rs $liters^{-1}$	22.3
Height	m	2
INITIAL TIME	Season	0
Installation cost 2003	Rs $unit^{-1}$	5900

Variable name	Unit	Equation
Irrigation efficiency zero time stock	Dimensionless	Irrigation efficiency zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'IEE' , 'b2*')
Kc	Dimensionless	Kc[Kccrop] = GET XLS CONSTANTS('?test', 'kc' , 'B2*')
Ky	Dimensionless	Ky[crops] = GET XLS CONSTANTS('?test', 'ky' , 'B2*')
Length	m	14
length in miles	m	length in miles[canal] = GET XLS CONSTANTS('?test', 'CL' , 'L2*')
Lining cost year 2003	Rs m^{-1}	59000
maintence cost year 2003	Rs $season^{-1}$ Nos^{-1}	7080
Maintence cost yesr 2003	Rs m^{-3}	590
maximum allowable number of tubewells	Nos	maximum allowable number of tubewells = 100
Minimum efficiency	Dimensionless	Minimum efficiency = 0.62
No of polygon over canal	Dimensionless	No of polygon over canal[canal] = 14,19,19,3,15,23,5,6,6,7,10,3,3,7,3,18,5,9,5,3,3
Nos of served polygon	Dimensionless	Nos of served polygon[canal] = 14,19,19,3,15,23,5,6,6,7,10,3,3,7,3,18,5,9,5,3,3
Percent of total income	Dimensionless	20
percentage losses lined	Dimensionless	0
percentage losses unlined	Dimensionless	0.44
Policy Canal lining	Dimensionless	Policy Canal lining[canal] = 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 Note: Individual canals lining policy can be evaluated by changing value from 0 to 1 for any particular canal
Policy Irrigation improvement	Dimensionless	0 or 1
Policy RH	Dimensionless	0 or 1
Polygon RD	m	Polygon RD[Polygon] = GET XLS CONSTANTS('?test', 'RD' , 'b2*')
Polygonal factor	Dimensionless	Polygonal factor[Polygon,canal] = GET XLS CONSTANTS('?test' , 'Active' , 'b2')
Pond cost year 2003	Rs m^{-3}	2950
RD	m	RD[Polygon] = GET XLS CONSTANTS('?test', 'RD' , 'b2*')
Sediment doposition rate	m^3 $season^{-1}$	0.021
SF	m $season^{-1}$	0.005
silted capacity zero time stock	m^3	Silted capacity zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'SC' , 'b2*')
Standard cost	Rs Nos^{-1}	56796
Standard depth	m	Standard depth = 6
Starting year	Dimensionless	Starting year = 1990
Sturcture life	season	Sturcture life = 30
Tank width	m	Tank width = 14
tanks per cell	Dimensionless	Tanks per cell = 1000
Threshold EC for tubewell installation	dS m^{-1}	Threshold EC for tubewell installation = 20

Variable name	Unit	Equation
TIME STEP	Season	1
Total length	m	Total length[canal] = GET XLS CONSTANTS('?test', 'CL' , 'b2*')
Tubewell number at zero time	Nos	Tubewell number at zero time[Polygon] = GET XLS CONSTANTS('?test', 'TWN' , 'b2*')
Water in storage zero time stock	m^3	Water in storage zero time stock[Polygon] = GET XLS CONSTANTS('?test', 'WIS' , 'b2*')
Width	m	5

6. Constants / Reality checks

Reality check	Unit	Equation
Check when RWH is not zero	-	Check when RWH is not zero[Polygon]: **THE CONDITION**:Policy RH=1: **IMPLIES**:Constructed capacity[Polygon]>=0:AND:Silted capacity[Polygon]>=0:AND:Actual RWH Costs[Polygon]>=0:AND:Construction Percentage[Polygon]>=0:AND:Actual costs maintenance RH[Polygon]>=0:AND:inflow[Polygon]>=0:AND:water in storage[Polygon]>=0: AND:Evaporation1[Polygon]>=0:AND:Seepage1[Polygon]>=0:AND:SS supply[Polygon]>=0:AND:Siltation rate[Polygon]>=0:AND:maintenance rate[Polygon]>=0:AND:Construction rate[Polygon]>=0:AND:Available capacity[Polygon]>=0:AND:Available canal supplies contributions to SS[Polygon]>=0:AND:Available runoff contribution to SS[Polygon]>=0
Check when RWH is zero	-	Check when RWH is zero[Polygon]: **THE CONDITION:** Policy RH=0: **IMPLIES:** Constructed capacity[Polygon]=0:AND:Silted capacity[Polygon]=0:AND:Actual RWH Costs[Polygon]=0:AND:Construction Percentage[Polygon]=0:AND:Actual costs maintenance RH[Polygon]=0:AND:inflow[Polygon]=0:AND:water in storage[Polygon]=0:AND: Evaporation1[Polygon]=0:AND:Seepage1[Polygon]=0:AND:SS supply[Polygon]=0:AND:Siltation rate[Polygon]=0:AND:maintenance rate[Polygon]=0:AND:Construction rate[Polygon]=0:AND:Available capacity[Polygon]=0:AND:Available canalsupplies contributions to SS[Polygon]=0:AND:Available runoff contribution to SS[Polygon]=0
Checking canal lining when policy is not zero	-	Checking canal lining when policy is not zero[canal]: **THE CONDITION:**Policy Canal lining[canal]=1: **IMPLIES:**Actual lining cost[canal]>=0:AND:canal decay rate[canal]>=0:AND:Canal lining[canal]>=0:AND:lined percentage[canal]>=0:AND:Lining rate[canal]>=0
Checking canal lining when policy is zero	-	Checking canal lining when policy is zero[canal]: **THE CONDITION:** Policy Canal lining[canal]=0: **IMPLIES:** Actual lining cost[canal]=0:AND:canal decay rate[canal]=0:AND:Canal lining[canal]=0:AND:lined percentage[canal]=0:AND:Lining rate[canal]=0
Conservation of mass check	-	Conservation of mass check[Ca4,N41,N49,N50]: **THE CONDITION:** Canal supply at head[Ca4]>=0: **IMPLIES:** Canal supply at head[Ca4]-canal evaporation[Ca4]=Canal seepage per polygon[N41]+Canal seepage per polygon[N49]+Canal seepage per polygon[N50]+canal supply in polygon[N41]+canal supply in polygon[N49]+canal supply in polygon[N50] Note: Same test was performed for all canal. Canal 4 is presented here as an example.
Constrained behavior limit test	-	Constrained behavior limit test[canal,Polygon]: **THE CONDITION:** Farm income[Polygon]=0: **IMPLIES:** Canal lining[canal]=0:AND:Tubewell discharge[Polygon]=0:AND:Constructed capacity[Polygon]=0:AND:Irrigation efficiency[Polygon]=0.6
Farm income is zero	-	Farm income is zero[Polygon]: **THE CONDITION:** Farm income[Polygon]=0: **IMPLIES:** Tubewell discharge[Polygon]=0
Negative behavior test crop1	-	Negative behavior test crop1[Polygon,canal,kc1,c1]: **THE CONDITION:** Canal supply at head[canal]=0:AND:Water requirment[Polygon]>0:AND:Policy RH=0: **IMPLIES:** Tubewell Nos[Polygon]>=0:AND:Crop area[Polygon,c1]>=0:AND:SS supply[Polygon]=0:AND:Water stress[Polygon,kc1,c1]>=0:AND:Salinity stress[Polygon,c1]>=0:AND:Farm income[Polygon]>=0
Negative behavior test crop2	-	Negative behavior test crop2[Polygon,canal,kc2,c2]: **THE CONDITION:** Canal supply at head[canal]=0:AND:Water requirment[Polygon]>0:AND:Policy RH=0: **IMPLIES:** Tubewell Nos[Polygon]>=0:AND:Crop area[Polygon,c2]>=0:AND:SS supply[Polygon]=0:AND:Water stress[Polygon,kc2,c2]>=0:AND:Salinity stress[Polygon,c2]>=0:AND:Farm income[Polygon]>=0
Negative behavior test crop3	-	Negative behavior test crop3[Polygon,canal,kc3,c3]: **THE CONDITION:**Canal supply at head[canal]=0:AND:Water requirment[Polygon]>0:AND:Policy RH=0:

Reality check	Unit	Equation
		IMPLIES: Tubewell Nos[Polygon]>=0:AND:Crop area[Polygon,c3]>=0:AND:SS supply[Polygon]=0:AND:Water stress[Polygon,kc3,c3]>=0:AND:Salinity stress[Polygon,c3]>=0:AND:Farm income[Polygon]>=0
Negative behavior test crop4	-	Negative behavior test crop4[Polygon,canal,kc4,c4]:THE CONDITION: Canal supply at head[canal]=0:AND:Water requirment[Polygon]>0:AND:Policy RH=0:IMPLIES:Tubewell Nos[Polygon]>=0:AND:Crop area[Polygon,c4]>=0:AND:SS supply[Polygon]=0:AND:Water stress[Polygon,kc4,c4]>=0:AND:Salinity stress[Polygon,c4]>=0:AND:Farm income[Polygon]>=0

7. Subscripts

Subscript	Unit	Equation
Canal		GET XLS SUBSCRIPT('?test' , 'Subscript', 'b1', 'b21' , 'Ca')
Crops		c1,c2,c3,c4
Kccrop		kc1,kc2,kc3,kc4
Polygon		GET XLS SUBSCRIPT('?test' , 'Subscript', 'a1', 'a215' , 'N')
position		Head,Middle,Tail

Subscript range

ShorkotdistryC1		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'b5', 'b18' , 'N')
MariminorC2		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'C5', 'C23' , 'N')
JalalpurminorC3		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'D5', 'D23' , 'N')
RajbanaMinorC4		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'E5', 'E7' , 'N')
LakiMrCa5		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'f5', 'f19' , 'N')
GaghDyCa6		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'G5', 'G27' , 'N')
KoraMrCa7		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'H5', 'H9' , 'N')
DauranpurMrCa8		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'I5', 'I10' , 'N')
PipliMrCa9		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'J5', 'J10' , 'N')
FaridMrCa10		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'K5', 'K11' , 'N')
RakhBhaMrCa11		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'L5', 'L14' , 'N')
KakiRMrCa12		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'M5', 'M7' , 'N')
KakiLMrCa13		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'N5', 'N7' , 'N')
BachrianwalaMrCa14		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'O5', 'O11' , 'N')
ArroutiMrCa15		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'P5', 'P7' , 'N')
HassuDyCa16		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'Q5', 'Q22' , 'N')
BasiraDyCa17		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'R5', 'R9' , 'N')
DarkhanaDyCa18		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'S5', 'S13' , 'N')
JaralaMrCa19		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'T5', 'T9' , 'N')
ModiMrCa20		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'U5', 'U7' , 'N')
DangraMrCa21		GET XLS SUBSCRIPT('?test' , 'Canalsvspolygon', 'V5', 'V7' , 'N')

CONNECTING TEXT TO CHAPTER 5

The physical processes and components of the final causal loop diagram, developed in Chapter 3, must be calibrated and parameterized for study area conditions, following the quantification of the socio-economic portion in Chapter 4. This chapter describes the application of a well-known and well-tested Spatial Agro Hydro Salinity Model (SAHYSMOD) to simulate physical components/variables in the semi-arid region of the Rechna Doab basin, Pakistan. A description of the physical model selection, theory, and data collection methodology is provided along with the use of the generalized likelihood uncertainty estimation (GLUE) technique for model calibration as well as uncertainty and sensitivity analysis.

This chapter was published in Journal of Environmental Modeling and Software (Inam et al. 2017). The format has been modified to be consistent within this thesis. All literature cited in this chapter is listed at the end of this chapter.

CHAPTER 5: **Parameter estimation and uncertainty analysis of the Spatial Agro Hydro Salinity Model (SAHYSMOD) in the semi-arid climate of Rechna Doab, Pakistan**

Azhar Inam, Jan Adamowski, Shiv Prasher, Raffaele Albano

Abstract:

Manual calibration of distributed models with many unknown parameters can result in problems of equifinality and high uncertainty. In this study, the Generalized Likelihood Uncertainty Estimation (GLUE) technique was used to address these issues through uncertainty and sensitivity analysis of a distributed watershed scale model (SAHYSMOD) for predicting changes in the groundwater levels of the Rechna Doab basin, Pakistan. The study proposes and then describes a stepwise methodology for SAHYSMOD uncertainty analysis that has not been explored in any study before. One thousand input data files created through Monte Carlo simulations were classified as behavior and non-behavior sets using threshold likelihood values. The model was calibrated (1983-1988) and validated (1998-2003) through satisfactory agreement between simulated and observed data. Acceptable values were observed in statistical performance indices i.e. Nash Sutcliffe efficiency (NSE), coefficient of determination (R^2), mean error (ME) and Root mean square error (RMSE). Approximately 70% of the observed groundwater level values fell within uncertainty bounds. Groundwater pumping (Gw) and saturated hydraulic conductivity (Kaq) were observed as highly sensitive, water holding capacity (Fs) and effective porosity of the aquifer (Peq) as moderately sensitive, and total porosity (Pt) and effective porosity as non-sensitive parameters affecting groundwater recharge.

Keywords: SAHYSMOD; Generalized Likelihood Uncertainty Estimation; Groundwater; Sensitivity analysis; Parameter estimation; Monte Carlo; Equifinality

5.1 Introduction

All models are coarse representations of real systems (Ciuffo *et al.* 2012) and high uncertainty levels can propagate to their output. Physical models, specifically spatially distributed surface and subsurface hydrological models, imply extensive epistemic uncertainties that need to be addressed in the modeling process (Walker *et al.* 2003). Generally, most model uncertainties are associated in specifying parameter values, model boundaries, and spatial variability (Hassan *et al.* 2008). Epistemic uncertainty (e.g. parameter uncertainty, boundary uncertainty, basic assumptions, and model resolution) can be reduced through improved data collection and measurement.

Computer technology advances in the development of versatile uncertainty estimation tools have helped researchers deal with high levels of uncertainty. Various uncertainty estimation techniques have been developed such as the Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Sequential Uncertainty Fitting (SUFI-2) (Abbaspour *et al.* 2004), Parameter Solution (ParaSol) (van Griensven and Meixner, 2006), Bayesian inference based on Markov chain Monte Carlo (MCMC) (Marshall *et al.* 2004; Vrugt *et al.* 2003; Yang *et al.* 2007) and Bayesian inference based on importance sampling (IS) (Kuczera and Parent, 1998). This study proposes the application of GLUE for predicting the uncertainty of groundwater levels in a distributed watershed scale surface and subsurface hydrological salt transport model (SAHYSMOD). Due to the unavailability of soil salinity data, uncertainty and sensitivity estimation was based on groundwater level fluctuation only and no salt data was simulated. GLUE accounts for uncertainty from all sources i.e. input uncertainty, structural uncertainty, parameter uncertainty and response uncertainty (Yang *et al.* 2008) and, unlike other techniques, it does not require prior knowledge of uncertainty in the model (Ciuffo *et al.* 2012).

The SAHYSMOD or Spatial Agro-Hydro-Salinity Model, was developed by the working group of the International Institute for Land Reclamation and Improvement (ILRI), The Netherlands (Oosterbaan, 1995). SAHYSMOD combines the agro-hydro-salinity model SALTMOD with the polygonal groundwater model SGMP. The model has many multidimensional management options that enable the user to evaluate different management scenarios, such as horizontal and vertical subsurface drainage, conjunctive water use, canal lining, controlled drainage and crop rotation. Generally, SHAYSMOD requires large datasets of water and salt transport parameters (e.g. soil moisture characteristics, dispersivity, and hydraulic conductivity), some of which are difficult to measure or estimate. Data for calibrating are often limited and input parameters are highly uncertain. A high level of uncertainty may produce unreliable results that make it difficult for policy makers to establish sustainable management solutions.

SAHYSMOD has received little attention since its development with limited research studies using the model (Akram *et al.* 2009; Desta, 2009; Laudien *et al.* 2008; Liaghat and Mashal, 2010; Singh and Panda, 2012). It has mainly been used in evaluating the effects of different management options on soil salinity distribution. With the exception of Desta (2009) and Singh and Panda (2012), all the aforementioned studies applied SAHSYMOD without calibration and validation procedures. For example, Akram *et al.* (2009) and Liaghat and Mashal (2010) applied SAHYSMOD to evaluate the performance of different bio-drainage system designs through simulation of groundwater levels and soil salinity changes, while Desta (2009) applied SAHYSMOD to model spatial and temporal variations under the semi-arid climate conditions of Thailand. Singh and Panda (2012) calibrated and validated SAHSYMOD specifically for Indian climatic conditions; however, they did not carry out an uncertainty analysis. Model calibration was done through trial and error runs of the model using arbitrary values of parameters. The concept of equifinality (Beven and Freer, 2001) is not recognized in trial and error calibrating processes, which may result in uncertain model simulation outputs. The present study is the first of its kind to explore uncertainty analysis for SAHYSMOD, and it will aid in the development of a procedure for SAHYSMOD users to investigate uncertainty in model results.

In this study, the SAHYSMOD model was applied to an irrigated semi-arid region located in a sub basin of Rechna Doab, Pakistan. Considering the cropping pattern in the study area, a year was split into two seasons of six-month duration. The model was simulated on a seasonal time step. As the model contains a large number of variables that are subject to spatial and temporal variations, each measured or estimated value is representative of the mean of a wide probability distribution with a large standard deviation. Furthermore, spatial interaction results in many variables and combinations that affect soil characteristics, thus making calibration a difficult task. To address the problem of equifinality, this study proposes the GLUE technique as an uncertainty procedure for SAHYSMOD; this technique will be helpful in evaluating uncertainties in model simulation before subsequent application for management scenarios. GLUE is a well-tested (Blasone et al. 2008; Fonseca et al. 2014; McMichael et al. 2006; Mirzaei et al. 2015) and structured method, proposed by Beven and Binley (1992). GLUE uses performance likelihood measures, based on a threshold Nash–Sutcliffe coefficient, to select acceptable data sets, and establishes uncertainty bounds for simulated values. Previous research studies (Akram et al. 2009; Desta, 2009; Kaledhonkar and Keshari, 2007; Laudien et al. 2008; Liaghat and Mashal, 2010; Singh and Panda, 2012b) have used SAHSYMOD for predicting soil salinity and groundwater level, without performing any uncertainty analyses. This study describes a stepwise methodology for SAHYSMOD uncertainty analysis that has not yet been explored in any study. The developed procedure may increase SAHYSMOD adoptability by helping users to investigate uncertainty in model results using a range of uncertain input parameters (such as hydraulic conductivity, porosity, drainage outflows and groundwater abstraction).

The main objective of this research was to apply, for the first time, the GLUE technique to SAHYSMOD for parameter estimation and uncertainty analysis. Moreover, sensitivity analysis was performed in order to evaluate the effect of calibrating the input parameters on groundwater level only. Due to the unavailability of soil salinity data, no salt data was simulated, and the uncertainty and sensitivity of leaching efficiency was not computed.

5.2 Materials and Methods

5.2.1 SAHYSMOD Description

SAHYSMOD is an agro hydro soil salinity simulation model that provides a simulation tool for evaluating different soil salinity management scenarios, using long-term simulations of aquifers and soil salinity changes in crop root zones (Oosterbaan, 1995). SAHYSMOD performs simulations on a seasonal time-step, using seasonal input data of salt and water balance for surface water hydrology (*e.g.* rainfall, potential evapotranspiration, irrigation, and run-off) and groundwater hydrology (*e.g.* groundwater pumping, capillary rise, and drainage). A year can be spilt into one (twelve months' duration) to four (three-months duration) seasons. The model uses a nodal network of rectangular polygonal configurations to define spatial variation in cropping, irrigation, drainage, and groundwater of the study area and takes a single average value at the centroid of each polygon. Average input values of groundwater level, rainfall, and salt content are estimated using ArcGIS at the centroid of each polygon, and are assumed to be the same over the whole polygon. For this purpose, ArcGIS built in tools such as Kriging, zonal statistics, extraction by attributes and conversion are used. The network neighborhood effect is defined through network representation, indicated through the polygon numbers. SAHYSMOD divides soil profiles into four layers *i.e.* surface, root zone, transition zone, and aquifer. The model then yields a comprehensive seasonal output, estimating changes in agricultural water, groundwater and salt balance for each layer, in each polygon. Salt and water changes are estimated through the conservation of mass principle, in which storage is positive if recharge is more than the discharge and vice versa. For more detail on SAHYSMOD, refer to Oosterban (1995).

5.2.1.1 Study area and SAHYSMOD configuration

The model was applied in the Rechna Doab sub-basin region of Pakistan, located downstream of the Ravi and Chenab rivers' confluence (inter-fluvial basin just above the intersection of two rivers) as shown in Figure 5.1.

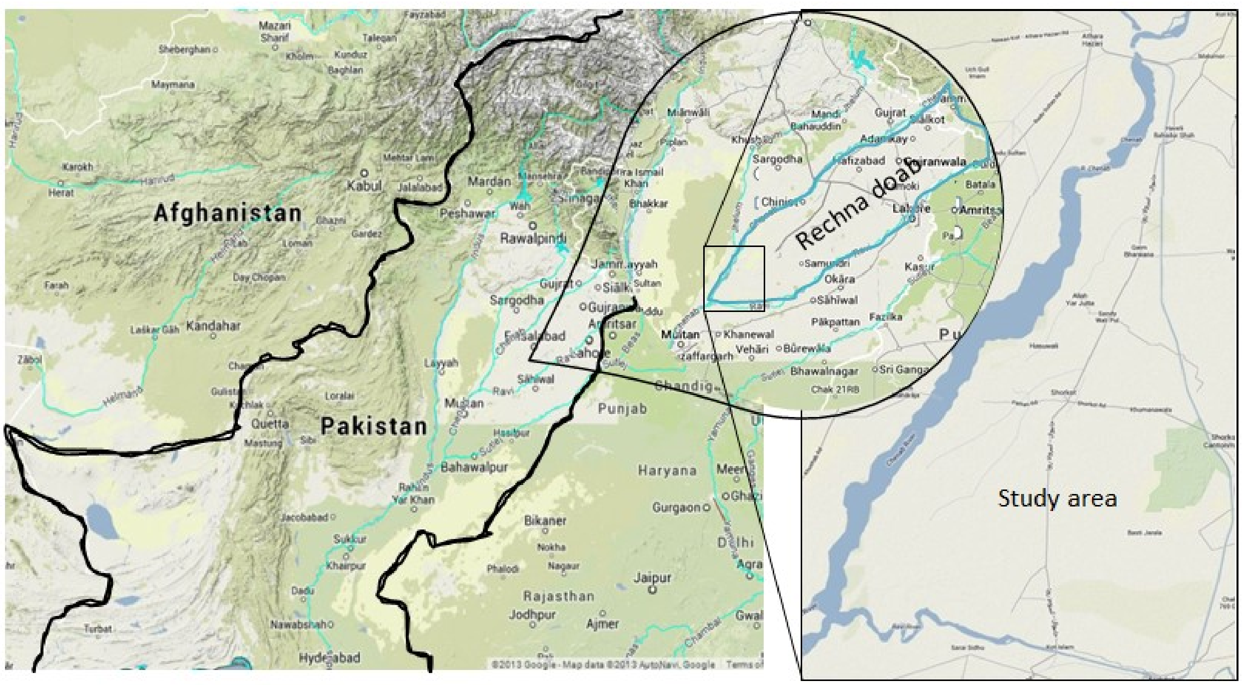


Figure 5.1. Study area in the Rechna Doab basin, Pakistan.

The Rechna Doab basin covers an area of about 732.5 km^2 and is served by the Haveli canal. While potentially cultivable, 30% of the area is barren due to high salinity. Soil salinity problems in the study region have been recorded as far back as 1890, due to the installation of large-scale irrigation systems without the provision of adequate drainage facilities. Although these large systems contributed to increases in crop production, problems of waterlogging and salinity have occurred because of intensive seepage from unlined canals. During the late twentieth century, the government of Pakistan initiated different salinity control and reclamation projects (*e.g.* SCARP). The SCARP-V project was implemented in the study area, where 368 large capacity wells (0.028 to 0.085 $m^3 sec^{-1}$) were installed for vertical drainage, as well as to augment existing water inputs. However, these wells soon became non-operative, due to high operation and maintenance costs.

Due to spatial variation in the soil series and cropping patterns, the study area was divided into a series of 279 rectangular polygons (215 internal and 64 external), each 21 × 21 cm in size (using a scale of 1:10000) (Figure 5.2). This is smaller than grids used in previous SAHYSMOD studies (Desta, 2009; Singh *et al.* 2012a) in order to give a more accurate presentation of catchment attributes.

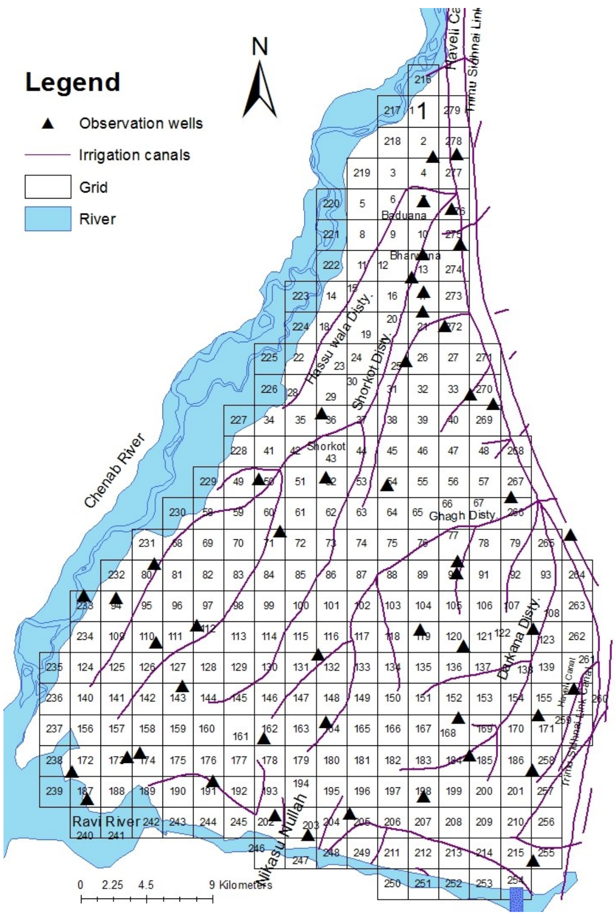


Figure 5.2. Nodal network polygonal configuration with observation wells and grid use in the SAHYSMOD model.

Each polygon acts as a separate unit, where nodal network relationships are used to model neighborhood effects. In some piezometers (observation wells), discontinuities were found in time series, mainly due to insufficient funding and malfunctioning or broken piezometers. Maintenance of Variance Extension technique type 4 (MOVE4), developed by Vogel and Stedinger (1985), was used to substitute 'no data' values and large gaps. It utilizes the correlation between the records at the piezometer of interest (or the dependent variable) and concurrent records at a highly-correlated piezometer (independent variable/predictor) to fill the data gaps. The technique is analogous to simple linear regression, with the advantage of maintaining the variance of the estimated records. Khalil and Adamowski (2014) showed that the simple linear regression and MOVE4 techniques have comparable precision and accuracy for the substitution of scattered missing data, however MOVE4 is more precise and accurate than simple regression in the case of larger gaps.

Data records of other hydrological variables, such as meteorological data, canal supplies, and irrigation water quality were complete. However, only two years of soil salinity data, extracted from remote sensing and aerial photographs, was available. Due to this lack of data, the model was not tested for soil salinity changes, and only groundwater levels were used for aquifer parameter estimation and uncertainty analysis. Point-to-point observation of different variables, such as hydraulic conductivity, porosity, effective porosity, and groundwater extraction potential was also not available. Hence, ranges for the these unknown variables were extracted from the literature (Khan *et al.* 2003; Mundorff *et al.* 1976; SMO, 1987) and used in GLUE for parameter estimation.

5.2.2 GLUE Description

Physically-based agro-hydro-salinity models, such as SAHYSMOD, can be difficult to calibrate, due to the requirement of large spatial and temporal datasets, which are usually not available. The models are also subject to uncertainty factors, such as the choice of boundary conditions, errors in input and observed variables, rainfall distribution patterns, and cluster or zoning method assumptions. In distributed models, estimated values of input variables are representative of the mean of a probability distribution, which can be wide. Hence, the calibration procedure is different from traditionally used approaches. Manual and automatic methods to calibrate distributed models focus on identifying a single parameter set that optimizes the agreement between observed and predicted values (Beven and Binley, 1992). In the case of SAHYSMOD, due to spatial interaction and high uncertainties, many variables and combinations might provide acceptable predictions rather than one optimal set. This is the concept of equifinality (Beven and Freer, 2001).

The GLUE methodology (Beven and Binley, 1992) explicitly recognizes the equifinality of parameter sets in physically-based modeling, and provides a more suitable framework for model calibration and uncertainty estimation. The GLUE methodology, implemented in the GlueWin (GLUE for Windows) software (Ratto and Saltelli, 2004), is used in this study to characterize uncertainty, error associated in model predictions, and parameter estimation for model calibration and validation. Implementing the GLUE methodology for alternative parameter sets requires the use of Monte Carlo simulations to generate a large number of alternative sets. Monte Carlo simulations create parameter sets using random sampling of the calibrating parameter space defined through the ranges (maximum and minimum limits) and probability distributions. The ranges are based on past research literature, project reports, and expert opinions. Since prior distribution of calibrating parameters (total porosity, effective porosity, storage efficiency and groundwater discharge) was not known, uniform distribution was chosen for its simplicity (Migliaccio and Chaubey, 2008; Shen *et al.* 2012). A log normal distribution was selected for random sampling of saturated hydraulic conductivity as it is generally considered the most appropriate probability distribution for representing saturated soil hydraulic conductivity. (Belcher *et al.* 2002; Mesquita *et al.* 2002).

5.2.3 Data acquisition and analysis

Over the course of the study period, spatial and temporal data sets on irrigation water supplies, soil type, hydrological characteristics, crop patterns, climate and aquifer properties were collected from different research organizations and government departments as well as research reports and district administration offices. Specific study area information, such as tubewell discharge, farm characteristics, irrigation practices, cultural practices, and management measures, were collected during the extensive stakeholder interviews conducted in the first phase of this study (Inam *et al.* 2015). The acquired data was stored, analyzed and processed using computer software (Microsoft Excel, ArcGIS, and Surfer) for estimation of the average seasonal conditions at the centroid of each polygon. Considering the seasonal input data requirements of SAHYSMOD, monthly meteorological data was used in the study. An overview of the collected data and their sources is presented in Table 5.1.

Table 5.1. Data acquisition sources and period for the SAHYSMOD modeling study

Data	Collecting method	Number of stations	Period (years)	Time step	Source

Meteorological data	Weather Stations	3	20 (1980-2010)	Monthly	PID, IWMI
Canal discharges	Gauging	All primary and secondary canals	20 (1980- 2010)	Daily	PID, IWMI
Irrigation water quality	Sampling	Primary canal	10 (1980-2010)	Seasonal	PID, DLR
Aquifer properties	Bore logs	12	-	-	hydrogeologic al directorate of WAPDA
Groundwater level	Piezometers	50	30 (1980-2010)*	Seasonal	SMO
Tubewell water quality	Samples	22	3 (2001-2003 & 2008	Yearly	SMO, DLR
Soil characteristics	Sampling	Study area	-	-	WASID, IWMI
Soil salinity	Visual observation, Arial photographs	Study area	2 (1981, 2003)	Yearly	DLR, SMO, IWMI
Cropping intensities	Remote sensing	Study area	1 (2003)	Seasonal	IWMI
Farm characteristics	Interviews	15 Farmers	-	-	Please see (Inam *et al.* 2015)
Irrigation practice	Interviews	15 Farmers	-	-	

*Data series from 1980-2003 were not complete. Data in the winter season of year 2005 and 2011 and in the summer season for year 1997, 2008, and 2010 was not observed due to shortage of funding.

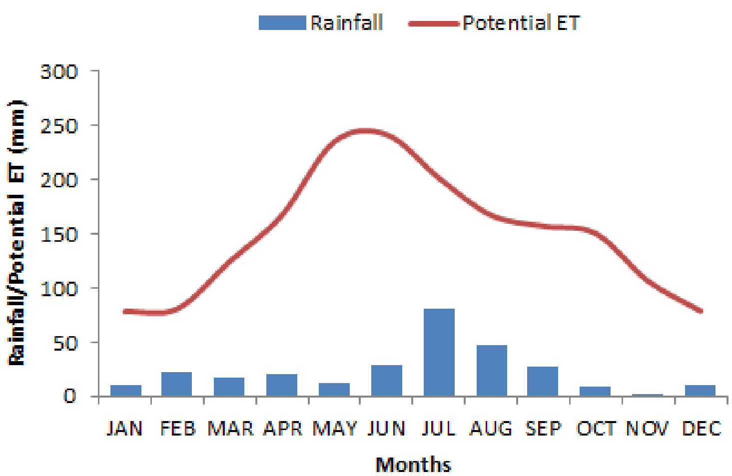
Data sources: International Water Management Institute (IWMI), Directorate of Land Reclamation (DLR), Soil Monitoring Organization (SMO), Punjab Irrigation Department (PID), Water And Power Development Authority (WAPDA), Pakistan Meteorological Department (PMD) and Water and Soil Investigating Division (WASID).

5.2.3.1 Topography

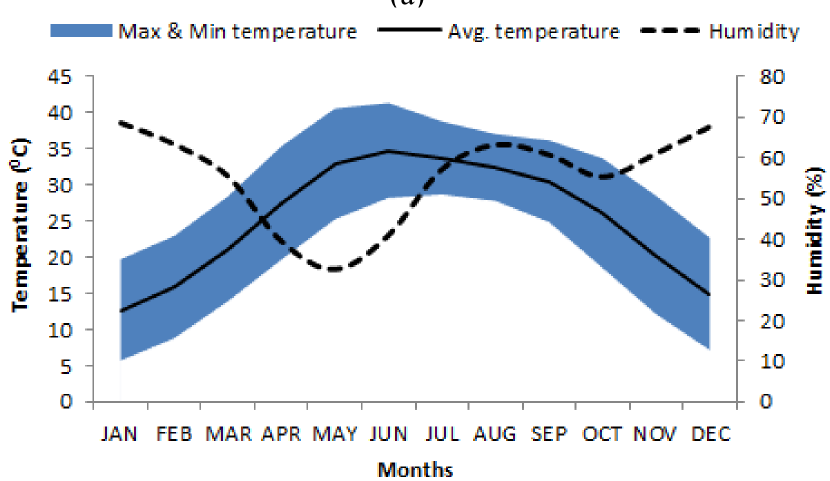
The project area lies between longitude 71^0 52' to 72^0 17' East and latitude 30^0 35' to 31^0 04' North. The area slopes in a south-westerly direction, with an elevation difference of 15 meters and an average slope of 0.21 m km^{-1}, along a 70km length. Considering flat topography, polygon size, and computational limitations, a 90m resolution Digital Elevation Model of Rechna Doab was acquired from the International Water Management Institute (IWMI) and was used to specify the spatial details of the polygons. The grid resolution selection follows the guideline of Dottori *et al.* (2013) and Yang *et al.* (2014) which recommends the use of coarser resolutions in flat areas in order to reduce computational burden.

5.2.3.2 Meteorological data

The study area lies within a semi-arid region, with an average annual rainfall of 290 mm; two-thirds of which occurs between June and September (Figure 5.3). There are substantial variations in temperature and rainfall, with the sporadic nature of the latter rendering it an unreliable source of irrigation water. Daily or weekly meteorological data was not available, hence monthly data on rainfall (mm), humidity (%), maximum and minimum temperature (^{0}C), wind speed, and sunshine hours for an extended period (1980-2010) were collected from the Pakistan Meteorological Department (PMD). In this study, observed values were used in the CROPWAT software (Clarke *et al.* 1998) to estimate reference evapotranspiration, using the Penman-Monteith equation. Figure 5.3 represents the long-term (30-year) mean monthly climatic characteristics of the study area.



(a)



(b)

Figure 5.3. Mean monthly (a) rainfall and evapotranspiration (b) Relative humidity, maximum

and minimum temperature of the study area

5.2.3.3 Irrigation data

Due to sporadic, inadequate rainfall, agricultural production in the study area is highly dependent on irrigation supplies from the canals. The main source is the Haveli Canal, which has a capacity of 208.78 $m^3 sec^{-1}$ at head, and a design allocation irrigation discharge of 35 $m^3 sec^{-1}$. The Haveli canal has an extensive irrigation network, with 15 channels and 325 outlets (Khan *et al.* 2003). Some channels are perennial (operate year-round) while others are non-perennial, operating for only 6 months due to inadequate water. Water from these irrigation systems is delivered on a rotational basis, called the "warabundi" system, where a farmer is allowed to take the entire flow of an outlet once every 7 to 10 days. Data such as channel water levels (m), irrigation water quality (dS m^{-1}), canal command area (m^2), and discharge rate ($m^3 sec^{-1}$) of all distributary, sub-branches and minor distributaries for the study period were collected from the Punjab Irrigation Department (PID). Information on the recharge rates of canals was not readily available, hence, the relationship developed by the Punjab Private Sector Groundwater Development Project (PPSGDP) (PPGDP, 1998) was used for estimating recharge to groundwater. The relationship is given below:

$$S_c = 0.052 \times {Q_c}^{0.658} \tag{5.1}$$

where S is the seepage in $ft^3 s^{-1} mile^{-1}$ (277.5 $m^3 season^{-1} m^{-1}$), and Q is the canal discharge in $ft^3 s^{-1}$ (446574 $m^3 season^{-1}$, the season being 182.6 days' duration). This equation is based on an empirical relationship for groundwater recharge estimation from the canals' discharge, and was developed through extensive seepage studies and historical data collected from a number of unlined canals in Rechna Doab.

5.2.3.4 Aquifer data

The study area is underlain by an unconfined aquifer (Khan *et al.* 2003), and the water table depth varies from 3-6 meters. Pumping tests conducted in the area by the Water and Soil Investigating Division (WASID) indicate the soil material is highly porous and capable of storing and transmitting water readily. Test well logs show that the minimum thickness of the alluvium layer is 200 m (Khan *et al.* 2003); the bulk of this (65 to 75 %) consisting of fine sand, with an absence of pure thick clay (Mundorff *et al.* 1976). For the current modeling study, an aquifer depth of 200 m was assumed. Average specific yield of the aquifer varies from 1 to 33 % (SMO, 1987), whereas the average values of hydraulic conductivities range from 26 to 158 m day^{-1} (Khan *et al.* 2003; SMO, 1987). In less permeable zones, this range is less than 26-52 m day^{-1} (Rehman *et al.* 1997). Detailed descriptions of the aquifer's hydrological properties are provided by Bennett *et al.* (1967). Groundwater quality is deteriorating in the central region of the study area, with dissolved solids concentration of more than 10,000 parts per million (ppm) observed in the saline areas. The Salinity Control and Reclamation Project (SCARP), and the Soil Monitoring Organization (SMO) installed 50 observation wells (See Figure 5.2) in the area, which monitor seasonal fluctuations twice a year (*i.e.* before and after the monsoon season). Thirty years (1990-2010) of observed piezometer levels were acquired from the SMO office, whereas bore log and other hydrogeological parameter data were obtained from the hydrogeological directorate of the Water and Power Development Authority (WAPDA).

5.2.3.5 Soil data

Alluvium deposits from the Indus River form soil in the area. The Water and Salinity Investigating Division (WASID) carried out extensive soil surveys and profile sampling of soil up to a depth of 180 cm. Based on the soil texture variation at a depth of 15-180 cm, they classified the study area soil into four groups as shown in Table 5.2.

Table 5.2. Texture classification of soils in the study area (Adopted from Khan *et al.* 2003)

Series (local name)	Texture Class	Texture
Jhang	Coarse	Sandy loam, Sand
Farida	Moderately Coarse	Sandy loam, Fine sandy loam
Buchiana	Medium	Loam, Silt loam, Silt
Chuharkana	Moderately fine	Sandy clay loam, Clay loam, Silty clay loam

A soil series map, developed for specifying the spatial distribution details of the soil classes, was obtained from WASID and processed in ArcGIS to find the percentage coverage area of each soil class in each polygon. The average soil class for each polygon was then determined using the area weighted average. For example, polygon 166 contains Chuharkana (45%) and Farida (55%) soil classes (See Figure 5.4). For the average soil hydraulic conductivity of polygon 166, hydraulic conductivities of the two soil groups were summed after taking the product of their respective hydraulic conductivities with their area fractions. The texture classification map of the area is shown in Figure 5.4.

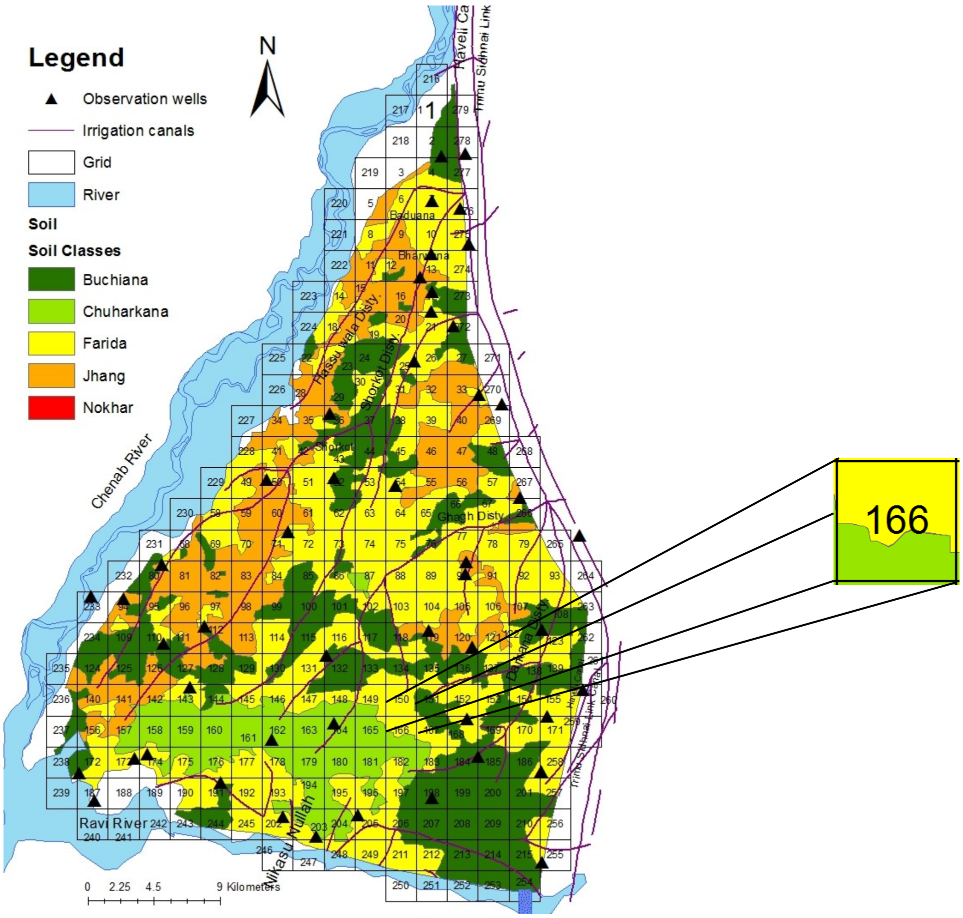


Figure 5.4. Soil classification map of the study area with nodal network numbers. Note: Polygon 166 has been zoomed out to elaborate the weighted average method and soil classification details.

5.2.3.6 Crop data

The study area lies in a semi-arid climatic zone, in which rice-wheat [Oryza sativa L. - Triticum æstivum L.], and cotton-sugarcane-cotton [Gossypium hirsutum L. - Saccharum officinarum L.] rotations are the most common. however, in some regions sugarcane is cultivated as an annual crop. The cropping year is divided into two seasons; Rabi (winter) from November to March, and Kharif (summer) from April to October. With wheat being the major crop, covering 80% of the study area, an average rooting depth of 1.5 m was considered acceptable for the specification of the crop root zone.

5.2.4 Calibrating variables

SAHYSMOD requires spatially distributed input data sets that are very difficult to observe on a watershed scale. Another layer of complexity in calibration is the spatial interaction between nodes. Some researchers (Akram *et al.* 2010, 2009; Desta, 2009; Liaghat and Mashal, 2010) used the SAHYSMOD model as a tool, without complete calibration, for evaluating different management approaches, while others (Singh *et al.* 2012a) performed calibration without uncertainty analysis. These studies used hydraulic conductivity (K), effective porosity (Peq) and leaching efficiency (Flq) as calibrating variables, and based on their analysis, hydraulic conductivity was found to be the most sensitive parameter.

For the present study, all readily available observed data sets were collected from different sources. Model calibration and uncertainty analysis were carried out with five major parameters that had readily available data: hydraulic conductivity, total porosity, effective porosity, storage efficiency, and groundwater discharge. SAHYSMOD considers storage efficiency separately for different cropping types *i.e.* A (a less water intensive crop), B (highly water intensive crop), and U (uncultivated land). Similarly, effective and total efficiency are defined separately for the root zone, transition zone and aquifer. Hence, for a homogenous soil polygon, the number of calibrating parameters, when split into groups, can be as high as eleven (Figure 5.7). Ranges of calibrating parameters were defined for each soil series. Ranges of soil parameters (effective and total porosity), tubewell numbers and pumping rate, and water storage efficiency were defined based on previous studies (Brouwer *et al.* 1989; Khan *et al.* 2003; Qureshi, 2011; REC, 1978; Saxton and Rawls, 2006) as well as expert advice. Values of saturated hydraulic conductivities were taken from previous project reports on the study area. Initial parameter ranges extracted from the above mentioned resources were used in the Monte Carlo simulation and optimized parameter values were obtained from the behavioral set having the maximum likelihood value. The behavior set with the maximum likelihood value is shown as a red dot in Figure 5.7. Table 5.3 lists ranges and optimized values of model calibrating parameters used in the study. The parameter ranges given in Table 5.3 were carefully selected from all available resources (experts, stakeholder interviews, literature) for rapid convergence of model results.

Table 5.3. Initial calibrating parameter ranges used in the Monte Carlo simulations and optimized ranges of behavior parameter sets.

Calibrating parameter	Initial minimum value	Initial maximum value	Optimized value	Probability distribution used
Jhang				
Ptr (%)	0.351	0.555	0.47	Uniform
Ptx (%)	0.368	0.506	0.39	Uniform
Ptq (%)	0.374	0.500	0.41	Uniform
K (m day^{-1})	26.00	158.0	51.71	Log normal
Farida				
Ptr	0.350	0.555	0.48	Uniform
Ptx	0.375	0.551	0.39	Uniform
Ptq	0.368	0.551	0.39	Uniform
K	26.00	120.0	48.48	Log normal
Buchiana				
Ptr	0.375	0.551	0.39	Uniform
Ptx	0.420	0.582	0.52	Uniform
Ptq	0.368	0.506	0.41	Uniform
K	26.00	103.0	35	Log normal
Chuharkana				
Ptr	0.332	0.464	0.35	Uniform
Ptx	0.412	0.522	0.50	Uniform
Ptq	0.375	0.551	0.53	Uniform
K	26.00	52.00	29	Log normal
FsA, FsB and FsU (%)	0.65	0.75	0.65 – 0.74	Uniform
P_e (%)	0.01	0.33	0.01 - 0.33	Uniform
Gw (m $season^{-1}$)	0.08	0.35	0.08-0.32	Uniform

The calibrating parameters given in Table 5.3, such as saturated hydraulic conductivity (K), total porosity (Pt) and effective porosity (Pe) of the root zone (r), transition zone (x) and aquifer (q) together defined the water conductance characteristics of the soil profile (see section 5.2.1). The remaining two parameters, storage efficiency (Fs) and groundwater discharge (Gw), were used to define soil water capacity and groundwater dynamics respectively.

In order to minimize the number of calibrating parameters, some assumptions were made. Since only a single year map of cropping patterns and intensities was available, the same cropping pattern was assumed to hold true for the following year; an assumption that was verified by the farmers during the stakeholder interviews. Wheat was the major crop (covering 80% of cropped area) in the region, and subsequently, the root zone depth was defined according to the rooting depth of wheat. The relationship developed by PPGDP (1998) was used to estimate the recharge component from the observed canal discharges. Observed water levels of the Ravi and Chenab rivers (which surround the study area) were not readily available, hence constant head boundary conditions were assumed using the observed groundwater levels of outer boundary polygons. Due to the flat topography, low hydraulic gradient and poor drainage conditions, surface inflow, outflow and drainage were assumed to be zero. Due to high pumping costs, and the non-operation of SCARP tubewells, it was assumed that farmers pump groundwater for irrigation purposes only. Hence F_w (the seasonal fraction of groundwater used for irrigation) was fixed as 1, where the value of F_w could vary from zero to one; zero indicated groundwater pumping for vertical drainage purposes only, while a value of one showed the use of the entire groundwater discharge for irrigation purposes. Due to the flat topography and unconfined aquifer conditions, constant inflow and outflow in the aquifer was taken as zero. These assumptions were further verified during the stakeholder interviews conducted in the first phase of the study (Inam *et al.* 2015), and through discussions with modeling experts in research organizations such as the Pakistan Council of Research in Water Resources (PCRWR), the IWMI and PPSGDP consultants.

5.2.5 Model calibration, testing, uncertainty and sensitivity analysis

The WinGlue methodology uses Monte Carlo simulations to produce a posteriori distribution, as well as confidence limits for evaluating maximum likelihood and generating uncertainty and sensitivity analyses. The proposed overall approach consists of four main steps: (i) clustering; (ii) Monte Carlo simulations; (iii) selection of behavior and non-behavior sets; and (iv) WinGlue analysis for maximum likelihood, uncertainty and sensitivity analyses. Finally, parameter sets with maximum likelihood values are used for model calibration and validation purposes. The overall process is illustrated in Figure 5.5.

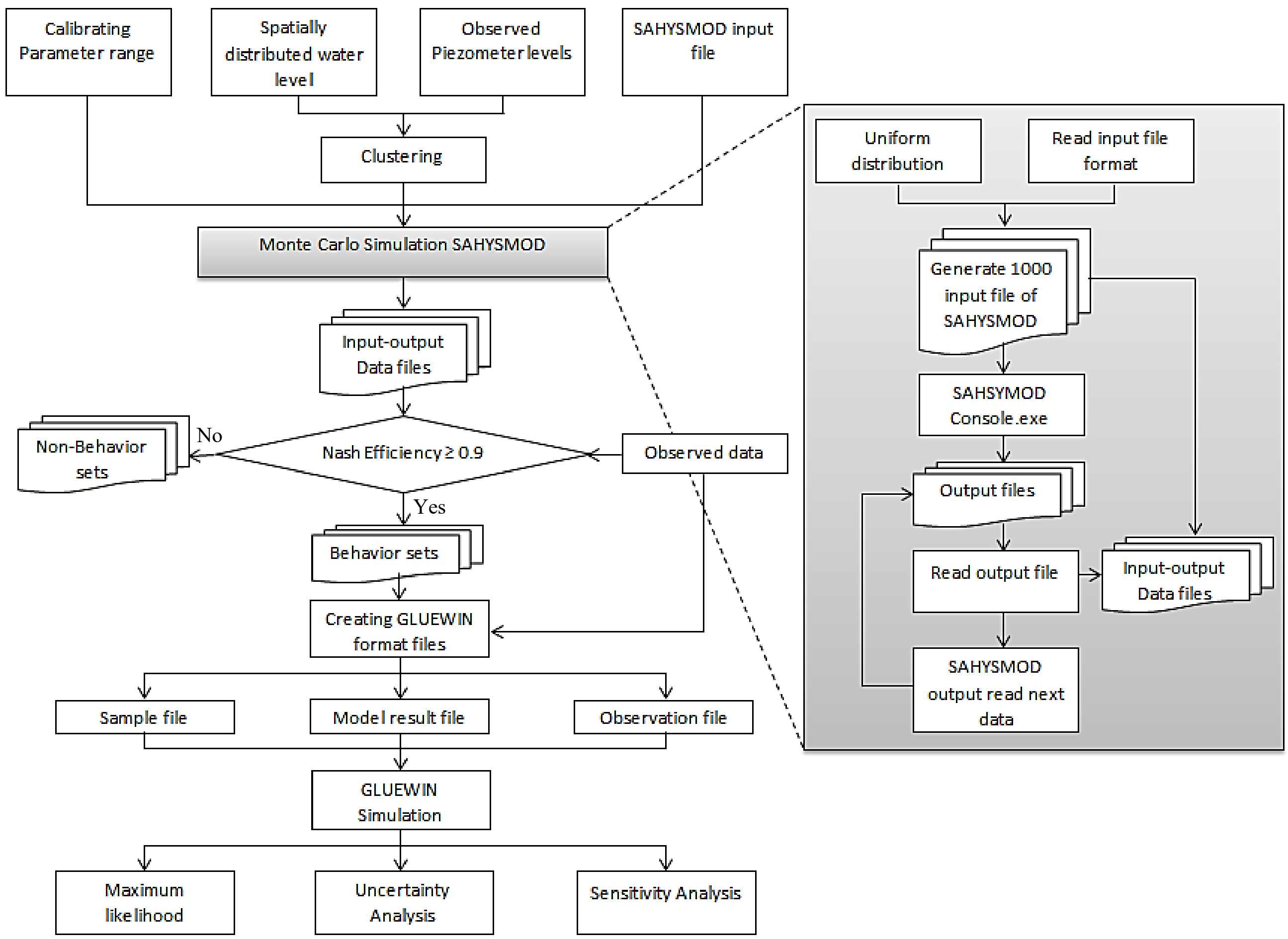


Figure 5.5. Flow chart of the proposed WinGlue approach with Monte Carlo simulation steps

5.2.5.1 Clustering

Clustering, also known as unsupervised classification, is used in identifying homogenous zones of observed groundwater levels through data grouping or pattern analysis. This provides an excellent tool for simplifying the calibration process of distributed models, by creating groups on the basis of variation in data trends, both spatially and temporally. The main advantage of using this method in the calibration of distributed models is the reduction in the number of parameters used in model calibration, thus addressing the problem of equifinality (Beven and Binley, 1992; Beven and Freer, 2001). For the current study observed and calibrated data variables were strongly dependent on groundwater level, hence clustering was done based on the spatial distribution of groundwater levels (*i.e.* the groundwater level value around each cluster had minimal variability). This arrangement reduces the number of calibration nodal points from 215 to 12, allowing the study to be conducted with reasonable computer resources. The K-mean function of MATLAB grouped polygons using observed piezometer data and interpolated groundwater level data in each polygon. The centroid of each cluster group (in this case, 12) was determined, and the model was calibrated using the observed data (from 1983 to 1988) of all piezometers at the cluster centroids. Figure 5.6 represents the numbers and grouping of clusters, with their centroids, over the study area.

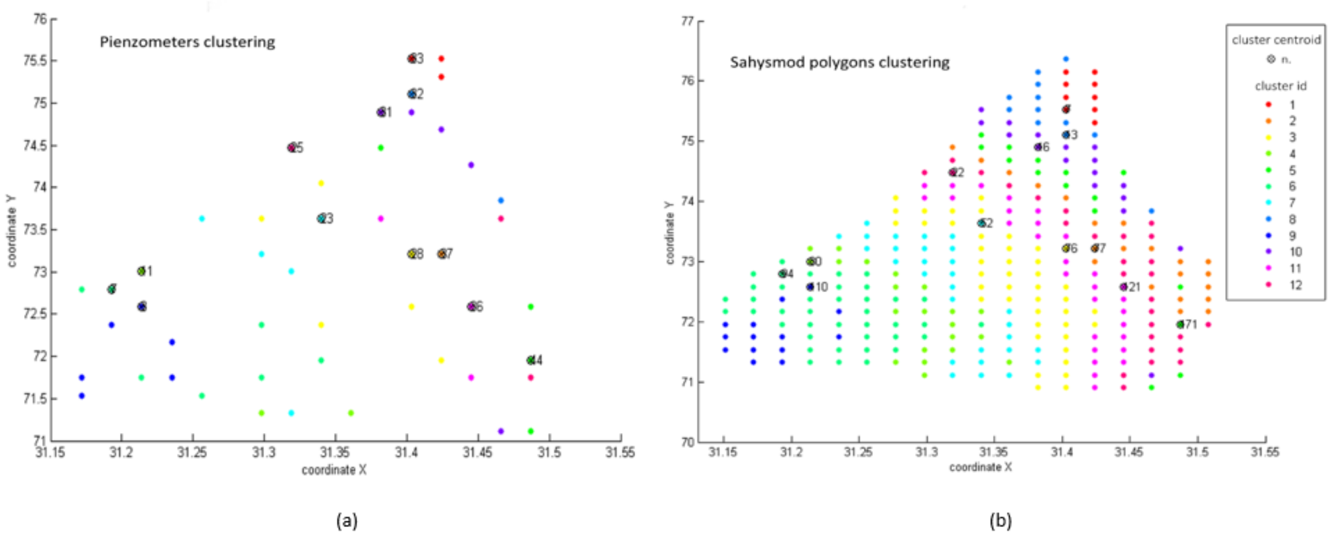


Figure 5.6. Observed piezometers (a) and SAHYSMOD polygons (b) with clustering groups used for model calibration. Note: Cluster groups are marked with different colors with numbers representing piezometer (a) and polygon (b) IDs at cluster centroids.

The number of cluster groups is dependent on groundwater variation, the size of the watershed, cropping intensity, land use, and soil class, with a maximum of fifty cluster zones created per number of observed piezometers. However, this may increase complexity and lead to problems of equifinality (Beven and Binley, 1992; Beven and Freer, 2001; Zak and Beven, 1999) without significantly improving model calibration. For the current study, the effect of increasing the number of clusters was evaluated by using 5, 8, 10, 12 and 15 clusters. Due to minimal changes in groundwater level (see section 5.2.3), low diversity (80% of the area is wheat crop), and similar cropping practices throughout the calibration period, a grouping of 12 clusters was found to be the most appropriate for testing the WinGlue application with SAHYSMOD for the study catchment.

5.2.5.2 Monte Carlo Simulations

The clustered zones, sample input file, and calibrating parameter ranges given in Table 5.3 were used to carry out the Monte Carlo simulations. The number of Monte Carlo simulation runs used for GLUE based distributed modeling studies is dependent on a number of factors, such as grid cell size, complexity and area of the study catchment, computing resources, model structure and model complexity. For example, some researchers have used tens of thousands or millions of runs for GLUE based studies (Brazier *et al.* 2000; Zak and Beven, 1999). However, their model code was less complex, their grid sizes were larger, the models were applied on small catchments and were computed with large, extensive computing power (e.g. high performance parallel processing machines comprising 18 PCs running Linux). Conversely, the current study was applied to a large catchment (732.5 km^2) with a small grid size (4.41 Km^2), which increases model complexity. The required time frame, as well as the available computing power further constrained the number of Monte Carlo simulations used in the study.

It is generally advisable to use more simulation runs to sample a high dimension parameter space with a large number of behavior parameter sets. However, in cases of constraint, using 1000 simulation runs is acceptable (Fonseca *et al.* 2014; McMichael *et al.* 2006). The calibrating parameter space, given in Table 5.3, was used to randomly sample parameters using uniform and log normal (for K) distributions. The Monte Carlo simulation engine coded in the MATLAB environment was then used to generate 1000 input files of SAHYSMOD for a five-year calibration period (1983-1988). Before selecting the calibrating period, tests such as checks for the dry and wet events through statistical tests of rainfall variability were carried out. Rainfall variability between the calibration and validation period was found to be insignificant ($P > 0.05$). Hence, the effect of alternating between calibration and validation periods was also considered insignificant. The selected calibrated data range contained the maximum number of observed data records with only a few missing slots (27 out of 612 records), which were filled using the MOVE 4 technique. Following the simulation of generated files, a data bank of input and corresponding output files was created.

5.2.5.3 Selection of behavior and non-behavior sets

The performance of each Monte Carlo simulation run was evaluated using the standard performance index from Nash and Sutcliffe (1970), the efficiency coefficient (NSE):

$$E = 1 - \frac{\sum_{j=1}^{n}\left(O_j - P_j\right)^2}{\sum_{j=1}^{n}\left(O_j - \bar{O}\right)^2} \tag{5.2}$$

where O is the observed groundwater level (m), $\bar{O}$ is the mean of the observed values, and P is the predicted values for n number of polygons. The value of efficiency (E) can vary from -∞ to 1. However, NSE values greater than 0.80 are considered satisfactory for simulation results (Andersen *et al.* 2001). The 1000 input-output data file sets generated through Monte Carlo simulations were further classified into behavior and non-behavior sets using the lumped NSE (i.e. estimated over the entire watershed using observed and predicted data of all 215 polygons) as the threshold likelihood measure. Behavior set are parameter sets that indicate good fits between the observed and simulated data where non-behavior sets does not indicate good fit. The threshold was set on a lumped model basis to improve model accuracy over the entire watershed. The following criteria was used for data file classification;

$$NSE_{lumped} \geq 0.90 \qquad Behavior\ \ sets \tag{5.3}$$

$$NSE_{lumped} < 0.90 \qquad Non-behavior\ \ sets \tag{5.4}$$

Where NSE_{lumped} indicates the lumped Nash and Sutcliffe efficiency estimated over the entire watershed using the observed and predicted data of all 215 polygons.

Behavior parameter sets selected in the preceding steps were used in the GLUE procedure to establish 95% and 5% uncertainty bounds. Upper and lower prediction limits of selected behavior sets represent uncertainty in the model output, due to uncertainty in model parameterization. Data that falls outside uncertainty bounds are due to errors in input data and observed variables. For the uncertainty analysis, behavior parameter sets were processed through MATLAB to create sample, observation, and output files for the WinGlue software. These files were used in WinGlue to establish the uncertainty bounds using a cumulative probability plot, which was created by graphing the cumulative sum of the likelihood values against the ranked model predictions. Further details on the procedure can be found in Beven and Binley (1992) and Beven and Freer (2001).

Sensitivity analysis was carried out via the WinGlue application to study the response of the calibrating parameters on the output of the variable of interest (*i.e.* groundwater level). The sensitivity analysis was carried out through the Kolmogrov-Smirnov two sample test (Spear and Hornberger, 1980). The test uses behavioral and non-behavioral parameter sets created using all parameters simultaneously. The sensitivity of a calibrating parameter was determined through the splitting of cumulative density plots of behavior and non-behavior parameter sets. If both cumulative density plots of the calibrating parameter of interest separated, then this parameter alone appeared to have a significant effect on the occurrence of behavior. The parameter was deemed sensitive and therefore worthy of observation, otherwise it was ignored. WinGlue, in addition to the quantified sensitivity results, also provided a visual sensitivity analysis through scatter plots.

5.2.5.4 Statistical error analysis

In addition to the NSE (Nash and Sutcliffe, 1970) used for the selection of behavior and non-behavior runs, the coefficient of determination (R^2), mean error (ME) and root mean square error (RMSE) were used to evaluate goodness of fit at the micro scale level i.e. at cluster centroids. Linear regression analysis was used to calculate R^2 values for macro scale evaluation i.e. using the observed and simulated data of all polygons. The coefficient of determination (R^2) is considered the most commonly used method for describing variance between simulated and observed values. It ranges from 0 to 1, where higher values represent good model performance, and an $R^2 > 0.5$ is generally considered satisfactory (Golmohamadi, 2014).

Mean error (ME) is an average of errors between the measured and simulated values and ranges from - ∞ to + ∞. Lower values of ME represent small variations between the observed and simulated values, thus deeming those model simulations as accurate. Negative values indicate an over prediction bias, while positive values represent under prediction. Root Mean Square Error (RMSE) is the standard deviation of the difference between simulated and observed values, where lower RMSE values indicate satisfactory model results (Singh and Panda, 2012a). The associated equations for these model performance error analyses are shown below:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad (5.5)$$

$$ME = \frac{1}{N}\sum_{i=1}^{N}(O_i - P_i) \quad (5.6)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{5.7}$$

where O_i and P_i are the observed and predicted groundwater levels of ith observation respectively. $\bar{O}$ and $\bar{P}$ are the means of the observed and simulated values. N is the total number of observed values and i varies from 1 to N.

5.3 Results and discussion

The performance of the Monte Carlo behavior sets was evaluated through likelihood values. Calibrating parameter ranges were graphed against likelihood values on scatter plots to ensure that all behavior sets were above the threshold likelihood value. Each dot on the scatter plots shows a model input set whose efficiency can be evaluated with associated likelihood values on the y-axis. Likelihood values of scatter plots were calculated using the observed and measured data of all polygons together i.e. it evaluated model results on a macro scale. Additionally, model performance at a micro scale i.e. at the centroid of each cluster, was evaluated through statistical error analysis. For this purpose, maximum likelihood input datasets (represented as a red dot on the scatter plot) were used for model calibration and validation purposes and the results were evaluated with statistical error parameters. Finally, uncertainty and sensitivity analysis of simulated results were carried out.

5.3.1 Scatter plot

Scatter plots give good visualizations of Monte Carlo simulation uniformity, density and performance, in terms of likelihood values. Likelihood values range from 0 to 1 (the closer the value to one, the better the model performance and vice versa). The performance of the model for 1000 behavior runs is shown in Figure 5.7. These scatter plots indicate the likelihood of different calibrating parameter values, *e.g.* the hydraulic conductivity plot in Figure 5.7 displays divergent behavior, which indicates that hydraulic conductivity at low ranges is more likely to produce good results.

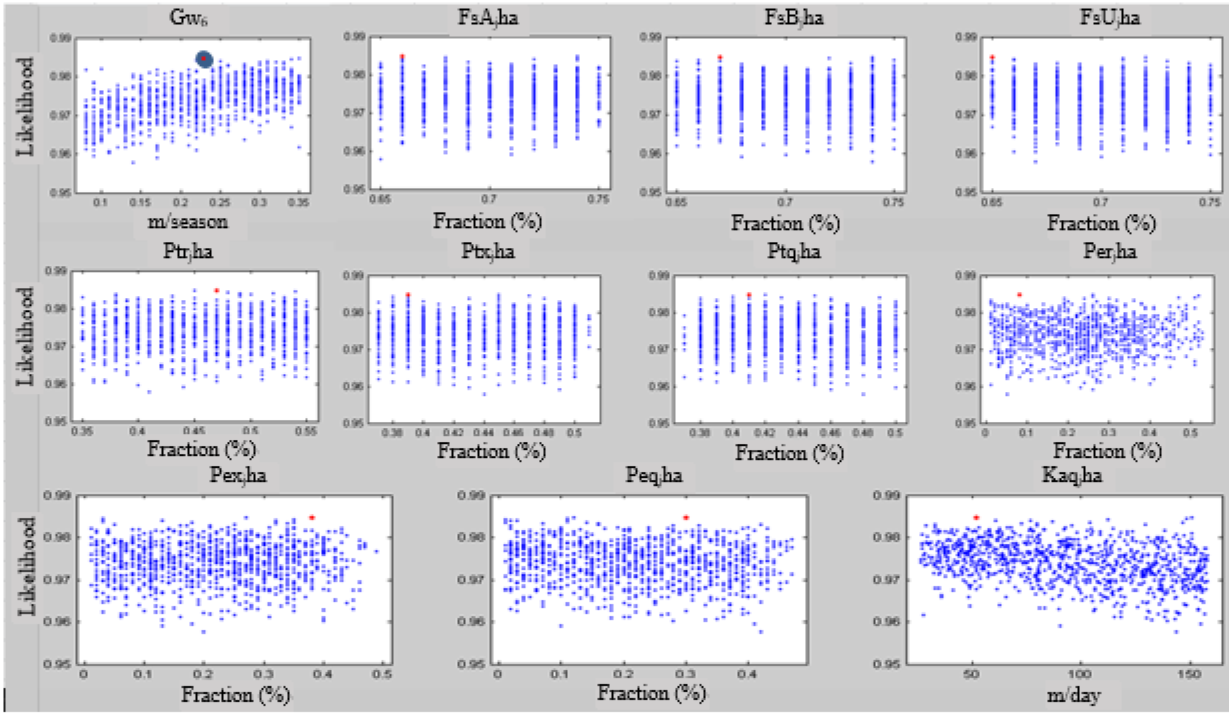


Figure 5.7. Scatter plots for the Jhang (coarse) soil group calibrating parameter sets using NSE as likelihood. Note: The red dot indicates the optimized value of the calibrating parameter against maximum likelihood. See section 5.2.4 for description of calibrating parameters.

Similar scatter and sensitivity plots for calibrating parameters were created for all four soil groups presented in Table 5.3, and the Jhang (coarse) soil group was selected for discussion (see Appendix 5A for scatter plots and Appendix 5B for sensitivity plots of remaining soil groups). Similar mapping characteristics, *i.e.* high density and uniform distribution, were observed in most of the plots, except the scatter plots of groundwater extraction (GW6) and saturated hydraulic conductivity (Kaq). Likelihood values varied from 0.96 to 0.985, which clearly indicate the expression of equifinality.

For parameter GW_6, which represents groundwater abstraction in cluster zone 6 (see Figure 5.6), likelihood values increased as groundwater abstraction rate increased (*i.e.* likelihood converges with high values of groundwater extraction). The trend observed in the scatter plot confirmed the field observation of canal water scarcity, and the high dependency of downstream farmers on groundwater resources. The plot also showed Gw = 2.3 as the most optimum value (Maximum likelihood) (indicated by a red dot in Figure 5.7); this was the value used for model calibration. The slope trend of the GW6 scatter plot highlighted it as a sensitive variable, and therefore it must be properly observed for better calibration results. In the case of saturated hydraulic conductivity, higher likelihood values were associated with low conductivity values; these likelihood values decreased as hydraulic conductivity increased. A value of 51.71 m day^{-1} was estimated as the most optimum, which was within the range taken from the field observations on the site (SMO, 1987). The non-horizontal trend of the scatter plot highlighted hydraulic conductivity's importance as a sensitive variable, and the need for it to be properly observed to allow for better calibration results. The remaining variables displayed horizontal trends with uniform distributions and were deemed insensitive.

5.3.2 Model Calibration and validation

Model calibration is essential for checking a model's performance, before it can reasonably be used to study the effect of different management scenarios. SAHYSMOD can reasonably simulate groundwater levels, as well as root zone soil salinity (Singh *et al.* 2012) but as the study area lies in a data limited watershed where soil salinity data was not readily available, observed groundwater levels records were used for model calibration and validation. The model was calibrated based on the period 1983-1988, using groundwater elevation records monitored biannually through piezometers/observation wells.

Model validation is an extension of model calibration that is necessary for evaluating a model's robustness under different operating conditions. For validation purposes, a small set of the calibrated runs was extracted using the higher threshold likelihood value i.e. NSE $\leq$ 0.95. Only 171 out of 1000 behavior sets passed the selection criteria. The 171 selected sets were considered more behavioral due to the high NSE value. In the model validation, each of the identified 171 behavioral parameter sets were used to make groundwater level predictions for the validation period 1998-2003 in order to evaluate their robustness under different conditions. Data ranging from 1998-2003 were selected as they provided the complete maximum observed records of all piezometer levels, with a wide range of variation in groundwater elevation levels due to climatic variations in wet and dry seasons.

The model calibration and validation results, in terms of seasonal time series plots of observed and simulated groundwater levels, are summarized in Figures 5.8. In both cases, the simulated data matches reasonably well for most of the polygons. The reliability of model outputs during calibration and validation runs was evaluated through statistical error analysis at cluster centroids, and complete model performance was judged using scatter plots (1:1 line) by plotting the simulated values of all nodes (215 polygons) against the observed groundwater levels. Statistical error analysis details at cluster centroids are summarized in Table 5.4, and lumped basis linear regression analysis results for model calibration and validations with consideration of observed and simulated data of all polygons are shown in Figure 5.9.

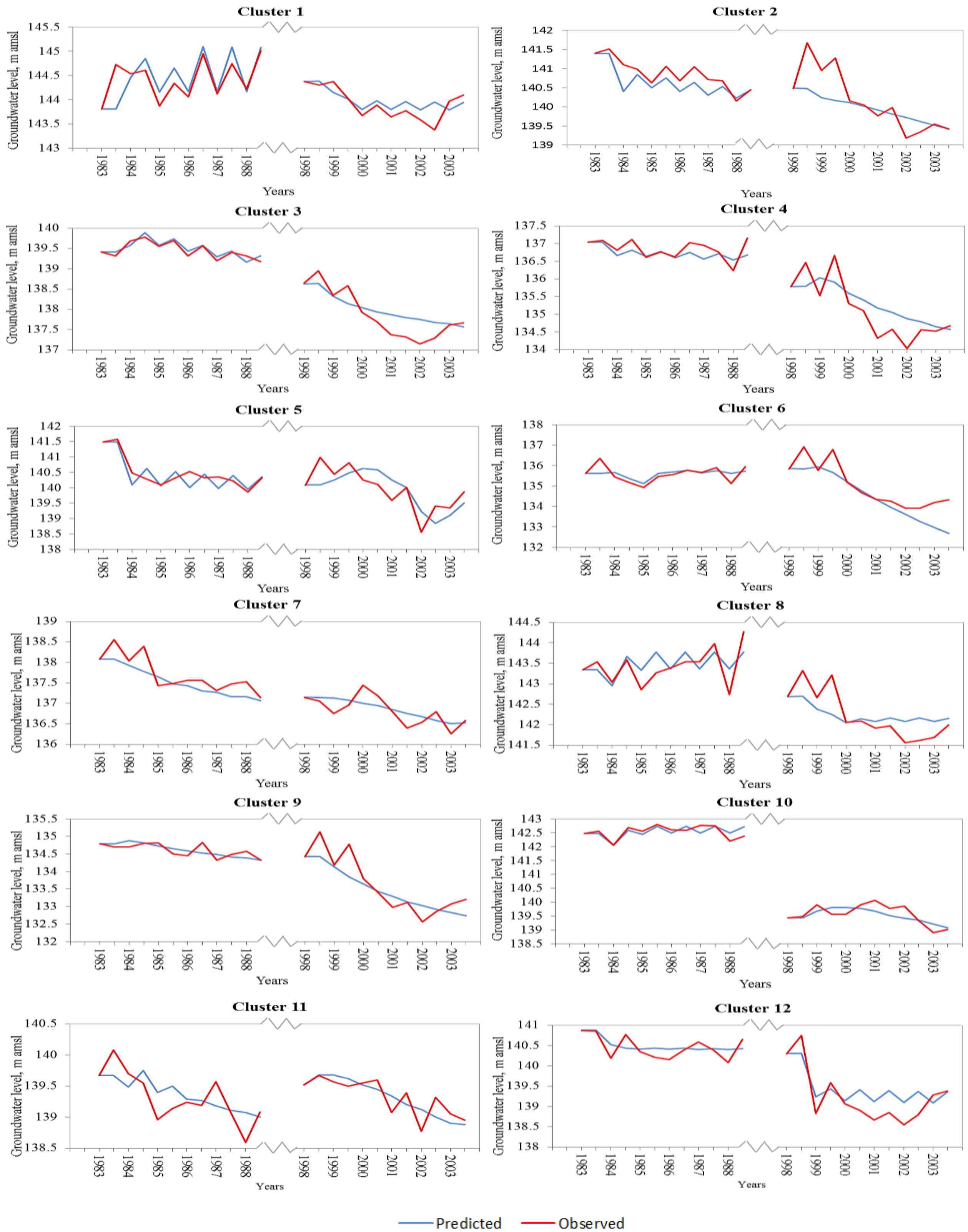


Figure 5.8. Observed and simulated groundwater elevations above mean sea level (amsl) at twelve clustering zones'centroids during the calibration (1983-1988) and validation period (1998-2003).

Slight deviations were observed in the results of clusters 7, 9 and 12 during the calibration simulations, and clusters 2, 3, 7 and 12 during the validation simulations. These deviations can be attributed to input data observational errors, uncertainties in groundwater extraction potential, as well as specific average soil water retention characteristics of the area. Another factor might be the use of coarser grid sizes, and the use of average (spatial) soil, crop, irrigation, and evapotranspiration conditions over the centroid of nodes. Deviations in simulated and observed values can also be linked to one major limitation of SAHYSMOD, the use of average (temporal) rainfall and evapotranspiration conditions for the entire simulation period. This limitation significantly affects the model simulation results, especially if the simulation period contained wet and dry years. No significant difference was observed in the patterns of observed and simulated groundwater levels, with an average fluctuation in groundwater levels of around one meter annually. The SAHYSMOD simulation successfully followed this observed groundwater fluctuation pattern, with shallow depths observed in the summer season (April to October) due to high rainfall. Overall, a decreasing trend in water table depth was observed, which was more pronounced in the middle and downstream regions of the study area.

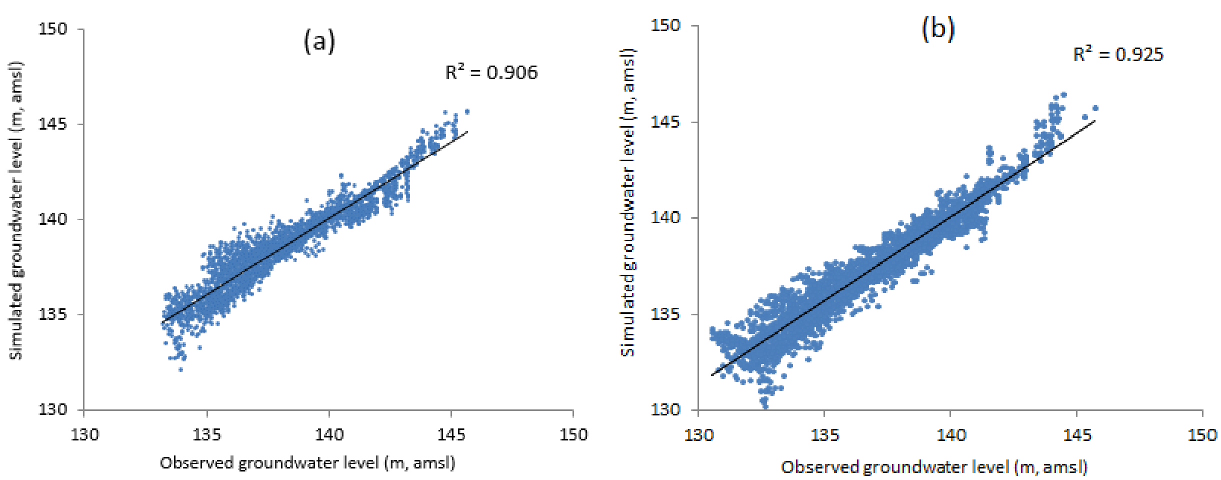


Figure 5.9. Scatter plot with linear regression with lumped R^2 of observed and simulated groundwater above mean sea level (amsl) during (a) calibration (b) validation periods.

An overall evaluation of the model displayed a reasonable fit between the observed data sets and the calibrated and validated groundwater levels. This can be further substantiated by high R^2 values of 0.906 during calibration, and 0.925 during the validation periods. The regression results showed that the model under predicts groundwater levels in the summer (when the levels are high) and over predicts them in the winter (when levels are low). These deviations can be attributed to the model's inherent limitations in simulating the effect of wet and dry periods, due to the use of average rainfall conditions.

Table 5.4. Statistics comparing measured and simulated groundwater elevation at the cluster centroid during calibration and validation periods.

Cluster	Calibration						Validation					
	NSE	R^2	ME	RMSE	$P_{0.05}$ slope	$P_{0.05}$ inter	NSE	R^2	ME	RMSE	$P_{0.05}$ slope	$P_{0.05}$ inter
1	0.319	0.537	-0.041	0.141	0.233	0.233	0.508	0.578	-0.073	0.254	0.591	0.591
2	0.364	0.710	0.213	0.737	0.542	0.540	0.489	0.714	0.195	0.675	0.040	0.040
3	**0.773**	**0.816**	-0.035	0.121	0.883	0.884	0.664	0.790	-0.122	0.423	0.149	0.149
4	0.181	0.374	0.113	0.393	0.612	0.613	0.590	0.683	-0.176	0.609	0.293	0.293
5	0.740	0.770	0.038	0.133	0.760	0.760	0.457	0.510	0.032	0.110	0.811	0.810
6	0.406	0.452	-0.017	0.059	0.554	0.555	0.425	0.732	0.504	1.746	0.143	0.144
7	0.547	0.729	0.181	0.625	**0.991**	**0.989**	0.497	0.510	**-0.038**	0.131	0.909	0.909
8	0.363	0.387	-0.063	0.220	0.869	0.869	0.440	0.595	-0.010	0.035	0.010	0.010
9	0.356	0.454	-0.008	**0.029**	0.283	0.282	**0.735**	0.790	0.141	0.487	0.465	0.465
10	0.398	0.434	**-0.005**	0.017	0.109	0.109	0.516	0.546	0.053	0.182	**0.960**	**0.960**
11	0.456	0.474	-0.046	0.158	0.540	0.538	0.574	0.621	0.004	**0.013**	0.397	0.397
12	0.376	0.409	-0.049	0.169	0.835	0.835	0.633	**0.791**	-0.193	0.667	0.376	0.377

Note: $P_{0.05}$ slope and $P_{0.05}$ intercept are regression analysis values of slope and intercept at $\alpha = 0.05$. Bold numbers indicate the cluster with the best value for each indicator of model fit.

Based on the R^2, NSE, ME and RMSE limits specified in the literature, performance indices indicated good simulation results. Table 5.4 shows the results during the calibration and validation periods. R^2 values varied from 0.374-0.816 and 0.498-0.791 during the calibration and validation periods (at the node centroids), respectively. The lower R^2 value in some clusters was mainly due to the distributed nature of the model where the nearest neighborhood effect created great complexities. For the distributed model Drécourt *et al.* (2006) highlighted the need for compromise between the model variability and statistical error analysis parameters. They stated that in focusing too much toward observed values, the model may become unstable and behave poorly over the rest of domain. Another reason for lower R^2 values was the high level of uncertainties involved in specifying soil hydrological parameters for different soil types and horizons for each polygon in the model. The ranges of soil hydrological parameters (P_e, P_t, K and F_s) were defined based on Saxton and Rawls (2006) study. The used ranges were based on very large data sets of soil determined through laboratory analysis of small soil samples. The model required elements at grid level scale, where both mean and variance may be significantly different. Moreover, uncertainties involved in the choice of boundary conditions, errors in input and observed variables, rainfall distribution patterns, and cluster or zoning method assumptions and use of MOVE4 to fill data in some missing slots of data also resulted in lower R^2 values in some clusters.

In this study R^2 values were higher than the limit of 0.50 for some of the clusters in the calibration phase, and in all clusters in the validation periods, thus indicating satisfactory results. ME ranged from -0.005 – 0.213 and -0.038 – 0.504 for the calibration and validation periods, respectively, with the lower ME values in both cases indicating reasonable simulation results. RMSE values varied between 0.029 – 0.737 and 0.013 – 1.746 for calibration and validation periods, respectively, indicating satisfactory simulation results. Furthermore, statistical analysis of the difference between the slopes and intercepts of fitted lines to the predicted and observed data was carried out through regression analysis. P values for slope and intercept varied from 0.109 to 0.991 and from 0.011 to 0.961 during the calibration and validation periods, respectively. Higher p values for slope and intercept differences indicated insignificant differences between the observed and simulated trends and intercepts, indicating satisfactory simulation results in terms of groundwater drawdown rates. Most of the clusters had no significant differences between the slopes or intercepts of the predicted and observed data ($p=0.05$).

Positive values of NSE were observed for all clusters during both calibration and validation periods, which indicates good agreement between the groundwater levels in the calibration and validation period. From the above statistical error analysis, a scatter plot regression analysis for all polygons was conducted, and the results are displayed in Figure 5.9. Based on this, it can be concluded that SAHYSMOD successfully simulated the groundwater levels in most of the polygons.

5.3.3 Uncertainty and sensitivity analysis

Uncertainty and sensitivity analyses are considered important steps in model development and evaluation. Uncertainty analysis is necessary for defining the uncertainty bounds of model outputs, whereas sensitivity analysis aids in the identification of the response of different inputs to model output in a particular study area. Generally, distributed models based on input from numerous parameters can produce equally acceptable outputs from different parameter sets, and a unique best set cannot be found in a given parameter space. Uncertainty analysis establishes uncertainty bounds using parameter sets, producing acceptable predictions based on threshold likelihood measures. For uncertainty analysis, selected behavior sets, filtered by specifying an NSE threshold of 0.90, were used to establish 95% and 5% uncertainty bounds. These represented prediction limits of model output associated with behavior parameter sets. The observed groundwater level values were compared with the corresponding uncertainty bounds and analysis for errors, with the results displayed in Figure 5.10.

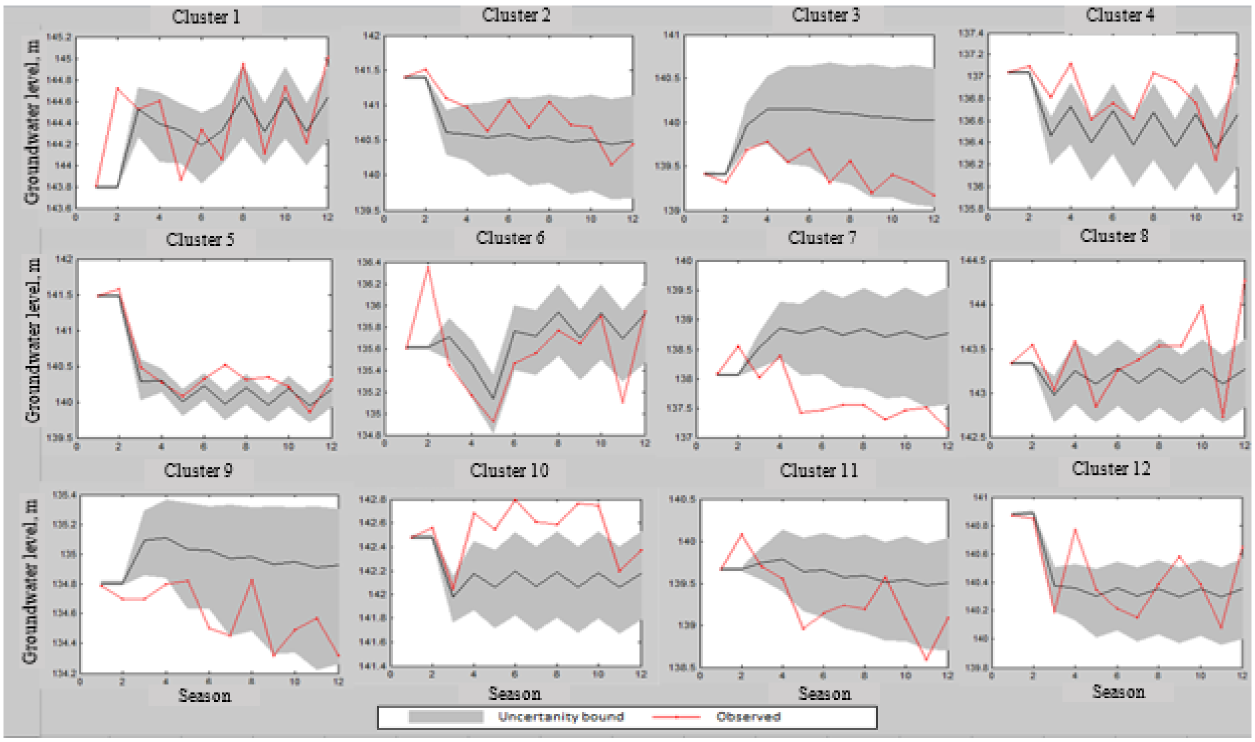


Figure 5.10. The 5% and 95% uncertainty bounds with observed groundwater levels during the calibration period.

Approximately 70% of the observed groundwater level values fell within uncertainty bounds. The remaining 30% represented prediction error, mainly due to uncertainty in model parameterization. Uncertainty bounds standard deviation varied from 0.01 m at the start, to 0.58 m at the end of the simulation period. As stated previously, the study area lies in a data limited watershed, and information on soil hydrological parameters, evapotranspiration, and groundwater extraction potential was not readily available. Hence, information on the surrounding area was used, which resulted in a high range of uncertainty. The observed groundwater level for nine of the twelve clusters fell within the uncertainty bounds, which indicates a good approximation of calibrating parameter ranges, and satisfactory simulations of the wet and dry cycle.

GlueWin produces visual sensitivity graphs in terms of cumulative distribution (see Figure 5.11). For the sensitivity analysis, the output from behavior runs was classified into two groups *i.e.* 50% smallest and 50% largest values. For the current study, sensitivity plots for calibrating parameters sets were created for all four soil groups.

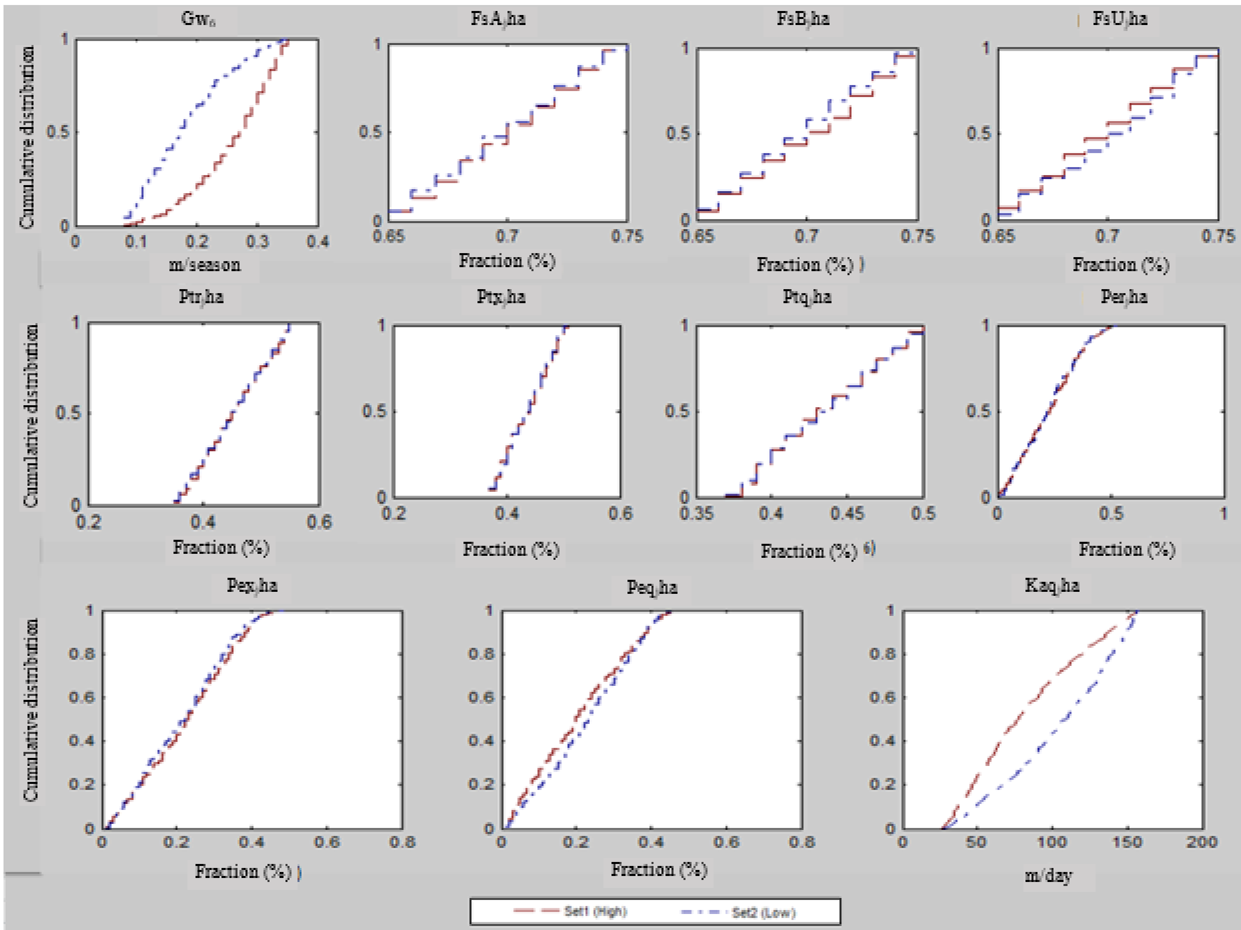


Figure 5.11. Sensitivity analysis of Jhang (coarse) soil group calibrating parameters sets Note: see section 5.2.4 for description of calibrating parameters.

The sensitivity of parameters was evaluated through 50% smallest and 50% largest cumulative distribution plots, and a parameter was deemed sensitive to output if the two cumulative distributions were far apart. If, however, the distributions were close, then the parameter was insensitive, and had minimal effect on model output.

The sensitivity analysis clearly demonstrated that groundwater pumping (Gw6) and saturated hydraulic conductivity (Kaq) were highly sensitive parameters that affected groundwater elevation, while moderate effects on water holding capacity (Fs) and effective porosity of the aquifer (Peq) were also observed. The model output was most sensitive to these parameters; therefore, they should be carefully monitored. However, total porosity (Pt) and effective porosity in the root and transition zones had little effect on model output. Similar kinds of sensitivity analysis patterns were observed in all other soil groups, and the results were in line with the findings of Singh *et al.* (2012a) who applied SAHYSMOD on an Indian watershed and found that the same sensitive parameter sets affected the output of groundwater levels.

The observed data indicated that groundwater levels were declining in the downstream region. In addition to other causes (e.g. low rainfall, poor recharge), it may be due to scarcity of canal water supplies which compel downstream farmers to meet their needs through the extraction of groundwater resources. The privatization of the large capacity wells (2.5-3.0 $m^3 sec^{-1}$) as part of the SCARP program in 1990 resulted in higher growth in the number of private tubewells (Qureshi *et al.* 2003). These private tubewells are now a significant source of irrigation water. Further lowering of the water table may affect the function of the wells, and consequently, the agricultural productivity of the area. One important factor that requires further study is the future change in spatial and temporal patterns of groundwater, under the influence of the rapid growth of private tubewells. Such growth may affect groundwater dynamics, as well as the salt balance of the area, by transporting salt to groundwater aquifers. Such a study will require a distributed model like SAHYSMOD for proper analysis.

The calibration, validation, and uncertainty results provided in the current study indicate that SAHYSMOD can be used effectively in data limited environments, such as the one in this study. Being a distributed model with multiple management options (canal lining, vertical and horizontal drainage, different cropping patterns), SAHYSMOD requires spatially distributed data sets, which are not readily available in many cases. Hence, the simulation results are subject to high uncertainty. For example, in the aforementioned proposed application, no data on private tubewell spatial and temporal growth patterns, nor extraction capacity, exists. Previous SAHYSMOD modeling studies used the model merely as a simulation management tool, without proper calibration, while others calibrated and used it for scenario analysis without conducting uncertainty analysis. The present study aids in bridging this gap, and shows that output obtained from data intensive distributed models display high levels of uncertainty, and require careful evaluation before the simulation results can be used to propose future recommendations. The study will also be helpful in the development of procedures for the use of distributed models, like SAHYSMOD, in data limited environments.

5.4 Conclusion

Physically-based agro-hydro-salinity models are known as effective management tools for simulating the salt and water balance within the crop root zone. However, the outputs of physical distributed models are subject to a high level of uncertainties, due to the choice of boundary conditions, errors in input and observed variables, land cover distribution patterns, and zoning method assumptions. Moreover, distributed models applied on large watersheds are difficult to calibrate, due to a need for large spatial and temporal data sets, which are usually not readily available. Additionally, traditional model calibration methods are quite difficult to apply, due to data limited environments. The current modeling study addresses the aforementioned issues by applying the GLUE technique on SAHYSMOD to evaluate changes in groundwater levels in the Haveli internal area of Rechna Doab, Pakistan. This study is the first of its kind to explore uncertainty analysis for SAHYSMOD, and will aid in the development of a procedure for SAHYSMOD users to investigate uncertainty in model results, by using ranges of uncertain input parameters, such as hydraulic conductivity, porosity, drainage outflows and groundwater abstraction. The application of the GLUE methodology proved to be a useful tool in modeling SAHYSMOD uncertainties and parameter sensitivities. This is useful in identifying the parameters that require greater attention in the case of financial and other constraints. The GLUE technique also recognizes the concept of equifinality and weighs possible parameter sets on the basis of the Nash-Sutcliffe efficiency coefficient.

The results of the current modelling study showed that the GLUE methodology works well, even in a data limited environment. Lumped model prediction compared reasonably well with observed data, yielding R^2 values of 0.906 and 0.925 for model calibration and validation, respectively. Uncertainty analysis results showed a reasonable estimate of uncertainty regarding coverage of observed groundwater levels, while sensitivity analysis identified saturated hydraulic conductivity and groundwater pumping potential as highly sensitive, and water holding capacity and effective porosity of aquifer, as moderately sensitive variables respectively. Also highlighted was the need to devote more attention to soil hydrological parameters for modeling agro-hydro-salinity environments.

The present study indicates the potential for using GLUE in data limited environments. While data collection is of great value, and cannot be truly replaced by statistical techniques, it requires a significant amount of resources in terms of time and money. In watersheds with high uncertainties and data limitations, GLUE may be helpful in identifing possible sources of error and in allocating more time and resources towards the collection of relevant data.

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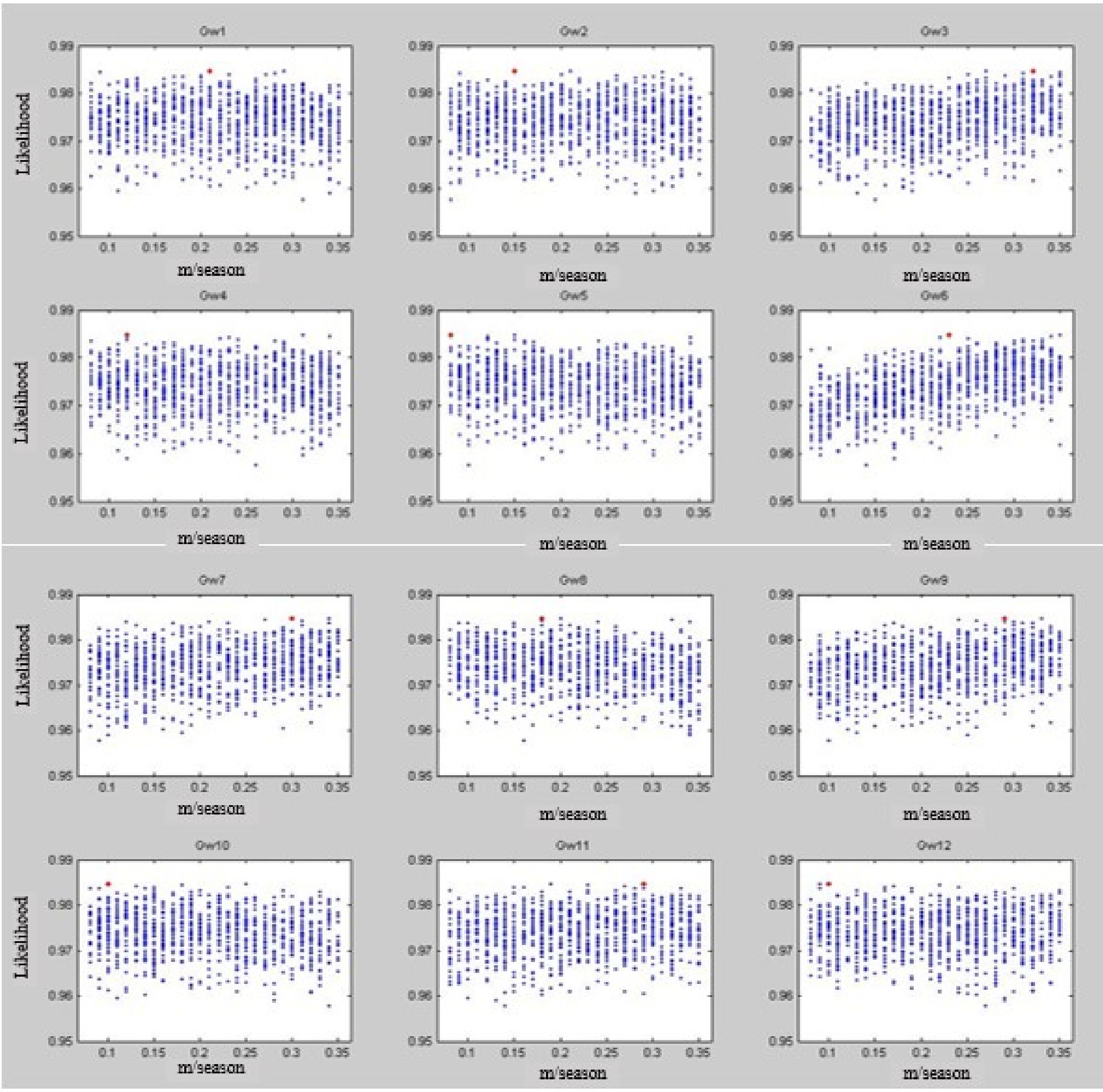
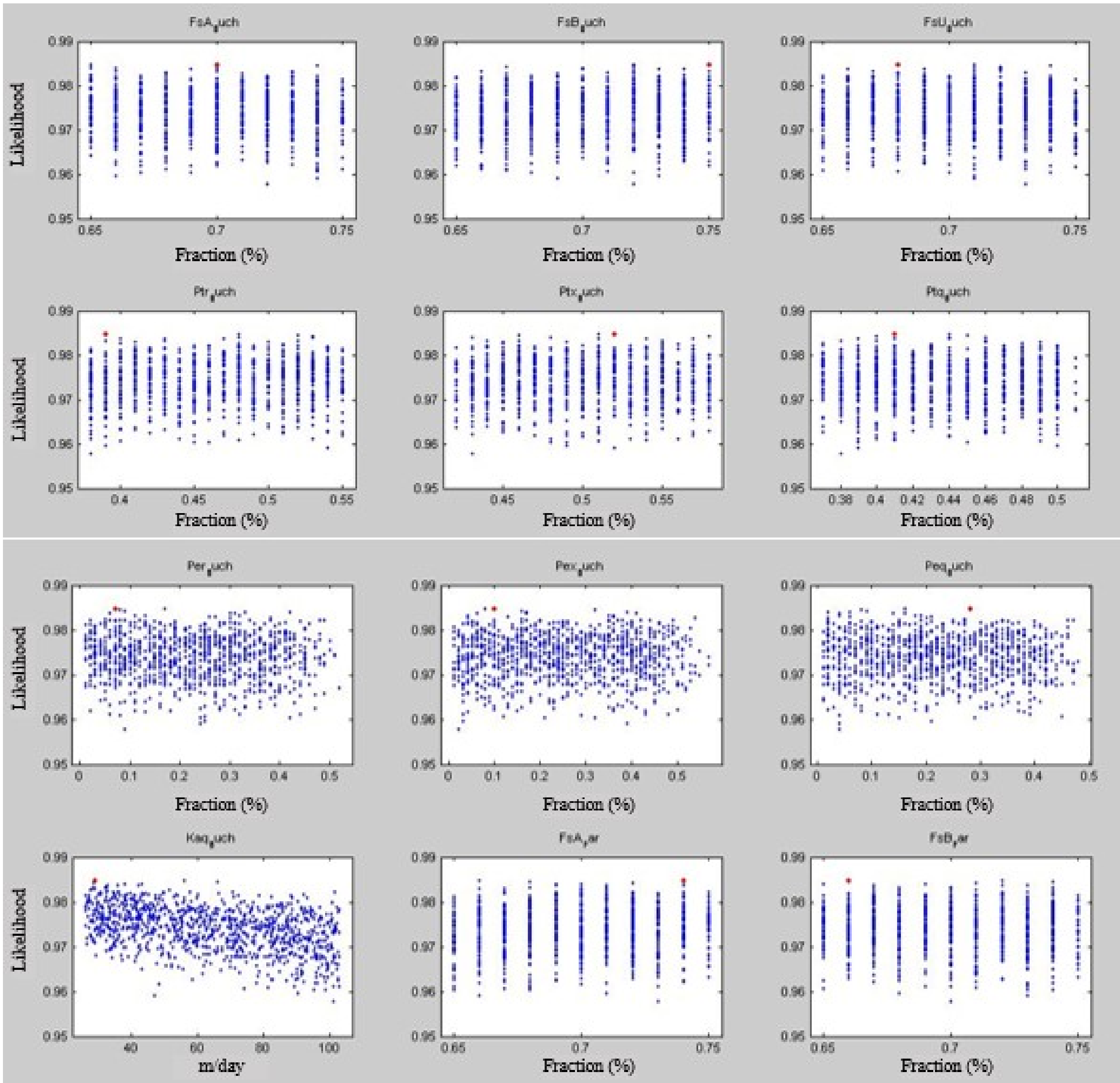
Appendix

Appendix 5A

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Likelihood
Fraction (%)
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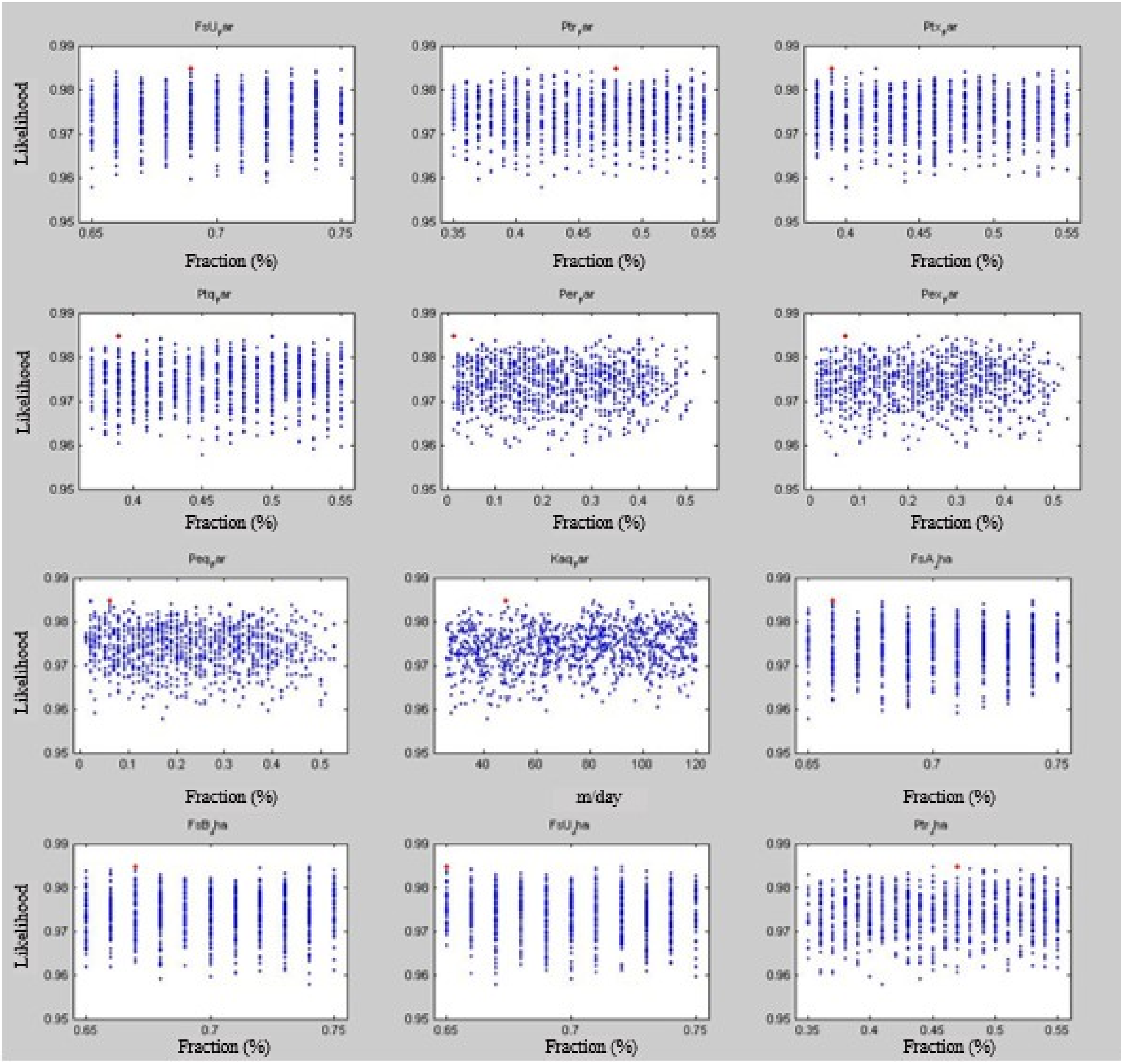
Likelihood
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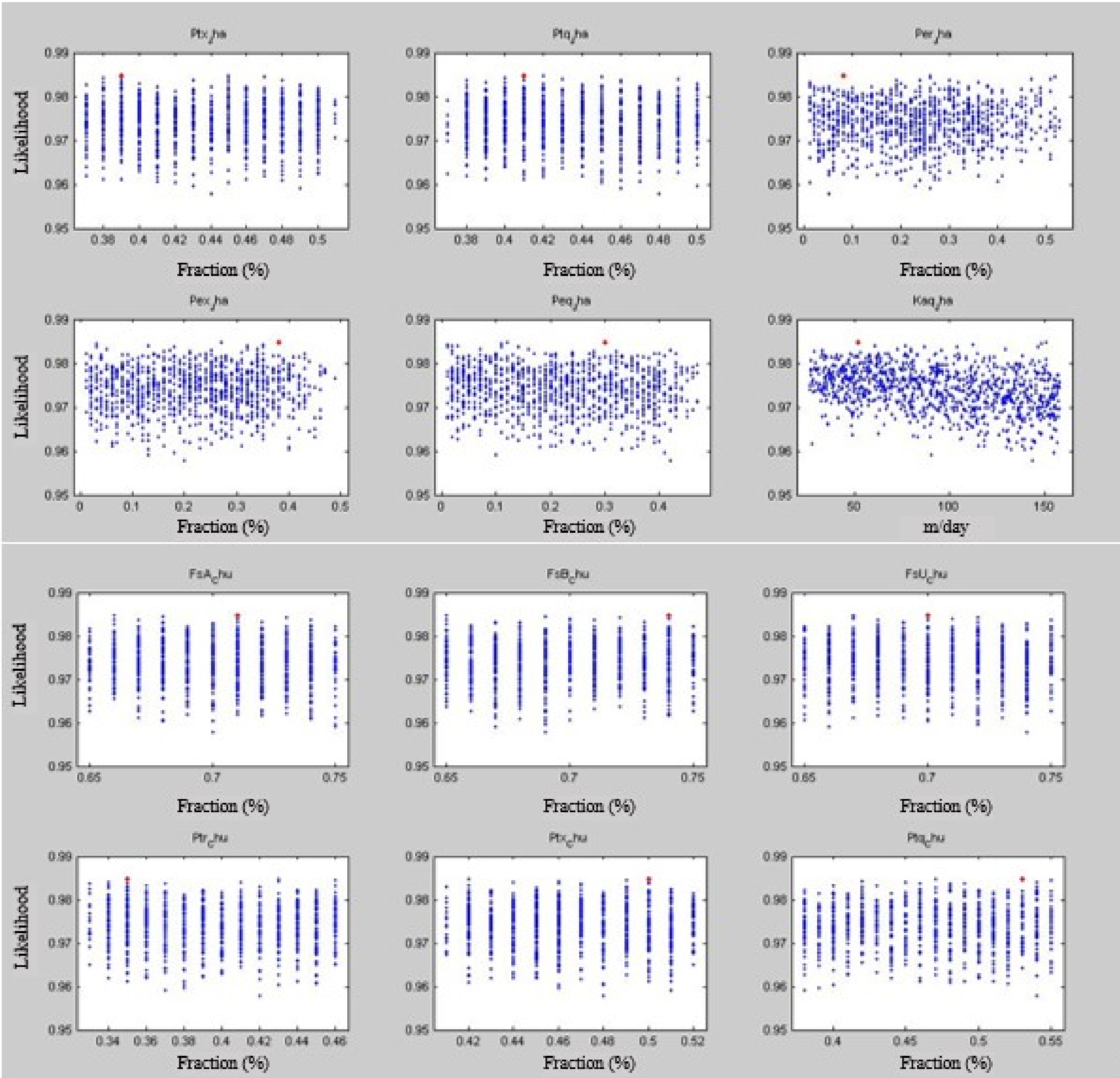

Likelihood
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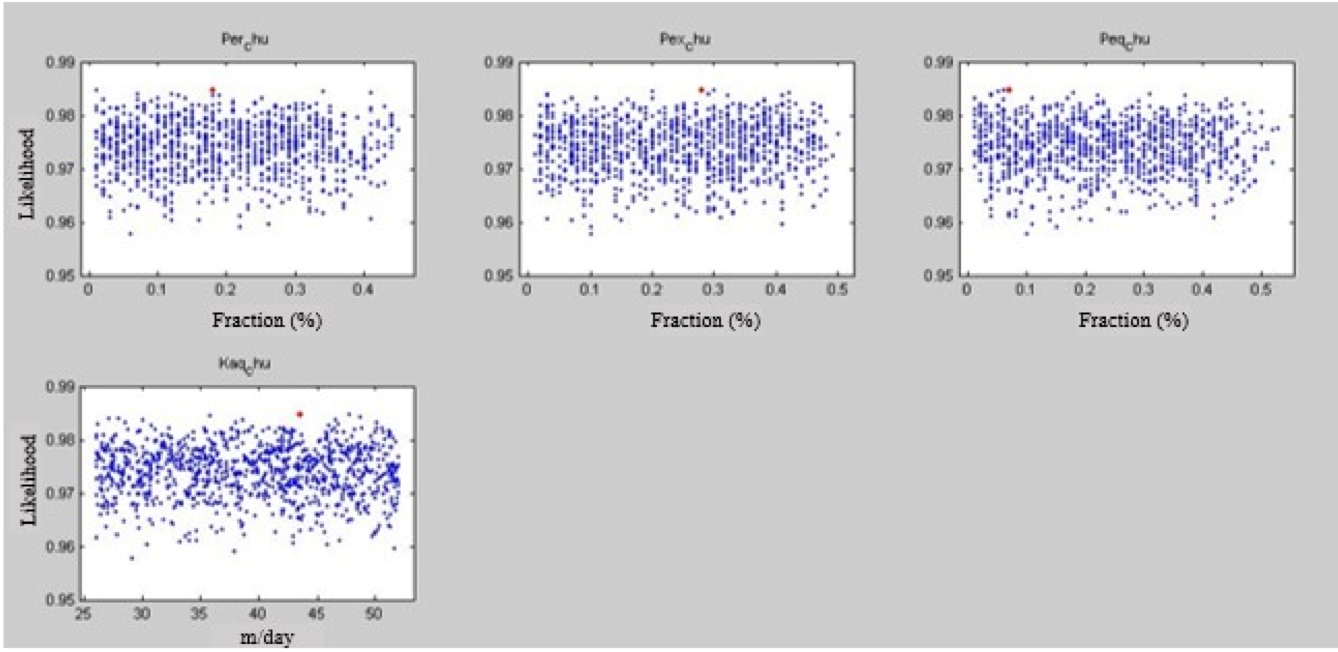
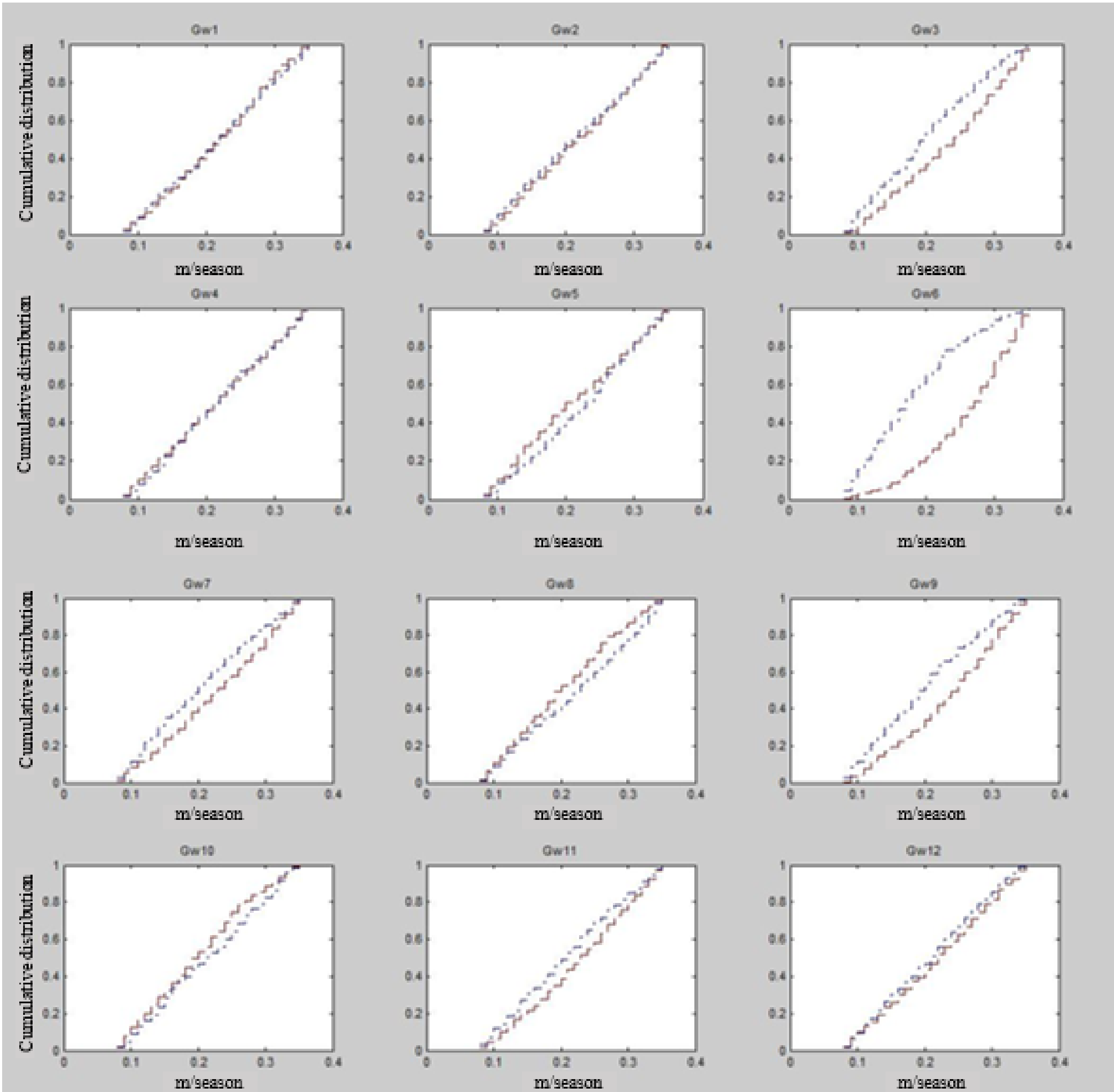


Scatter plots of calibrating variable for different soil groups

Appendix 5B


Gw1
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Cumulative distribution
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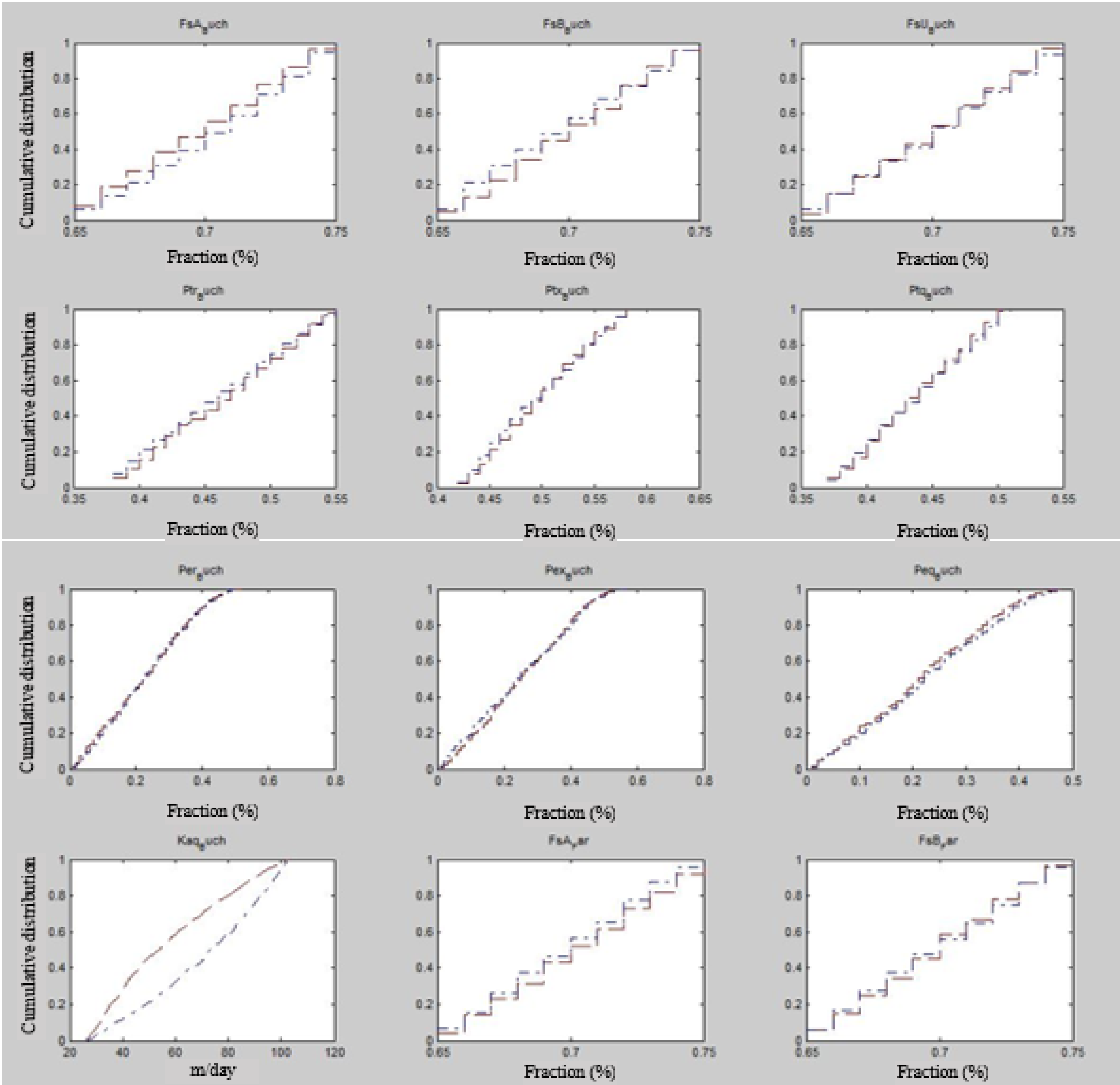
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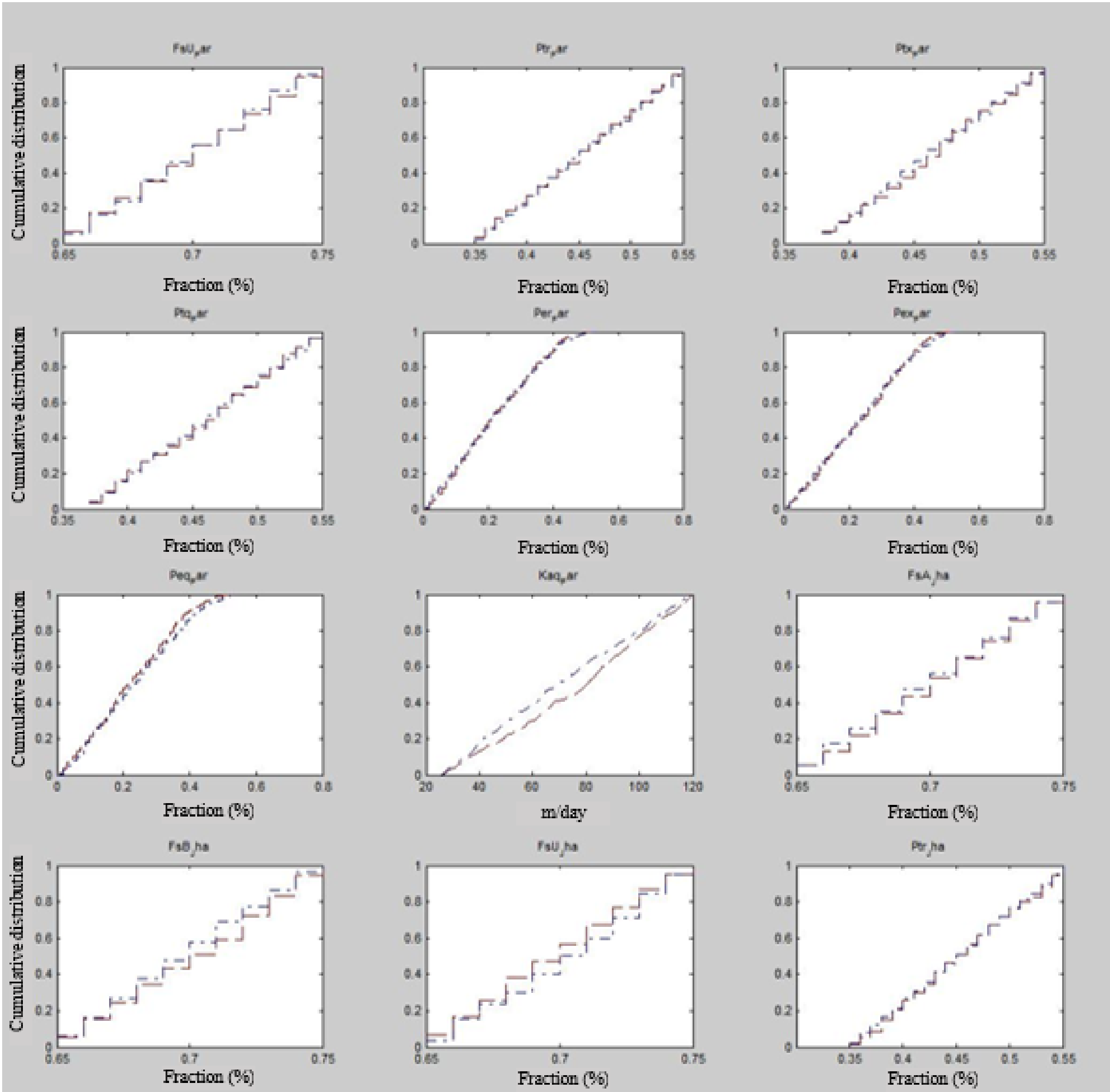
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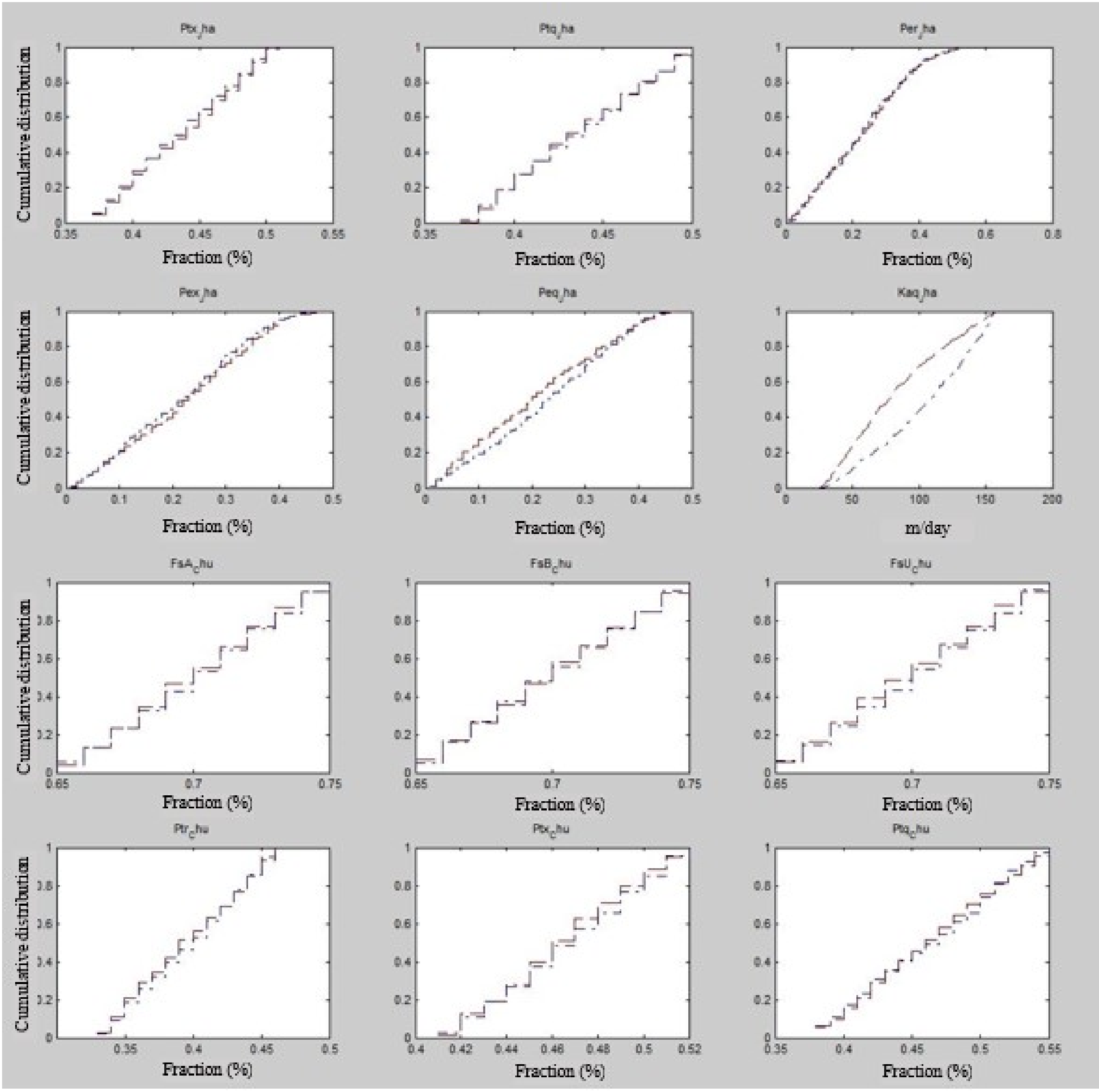

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Cumulative distribution
Fraction (%)
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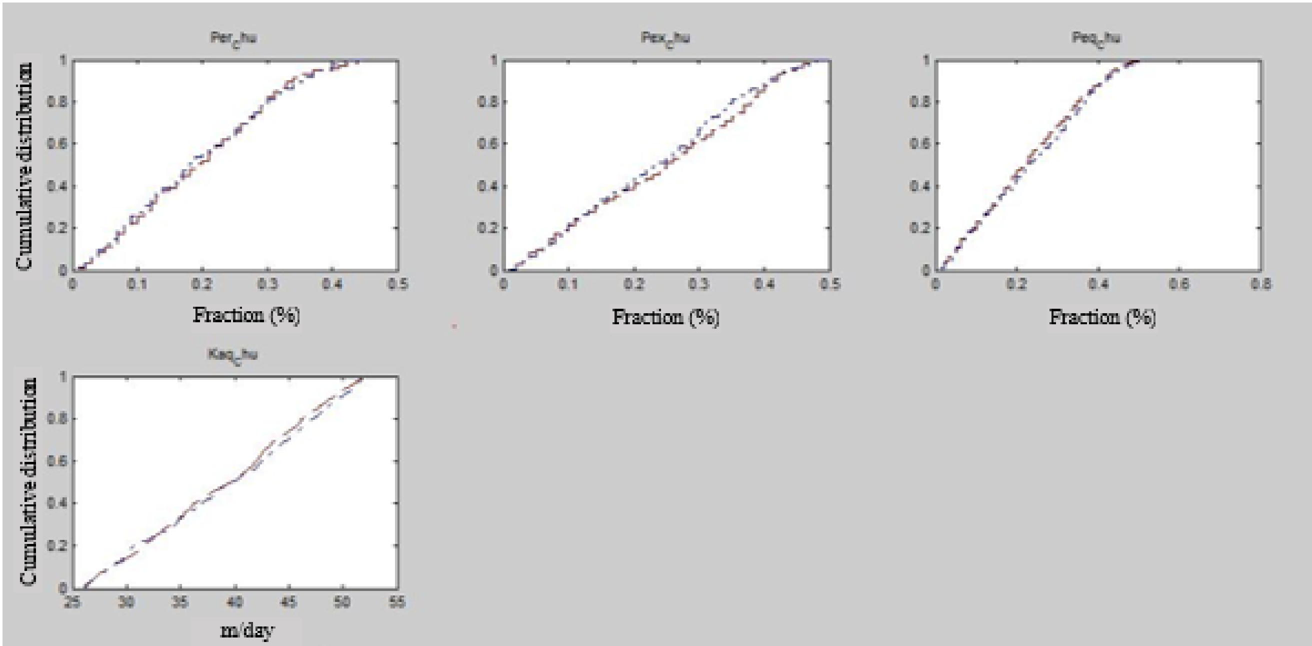


Sensitivity plots of calibrating variable for different soil groups

CONNECTING TEXT TO CHAPTER 6

The socio-economic model quantified in Chapter 4, and the physical model calibrated and validated in Chapter 5, must be linked together in order to dynamically simulate the complete system and evaluate the effects of stakeholders recommended policies. This chapter describes in detail the linking approach, interchange of variables, and model linking structure. Use of the integrated model for the evaluation of six alternative management scenarios is discussed. Spatial maps of soil salinity, water availability, and farm income and the economic and environmental trade-offs of different management scenarios are presented.

This chapter was published in the Journal of Hydrology (Inam et al. 2017). The format has been modified to be consistent within this thesis. All literature cited in this chapter is listed at the end of this chapter.

CHAPTER 6: **Coupling of a Distributed Stakeholder-Built System Dynamics Socio-Economic Model with SAHYSMOD for Sustainable Soil Salinity Management. Part 2: Model Coupling and Application**

Azhar Inam[1], Jan Adamowski[2], Shiv Prasher[3], Johannes Halbe[4], Julien Malard[5], Raffaele Albano[6]

Abstract

System sustainability depends on a complete understanding of the interactions between socio-economic and physical processes. However, many simulation models focus on simulating a single physical process and do not constitute balanced representations of the physical, social and economic components of a system. The present study addresses this challenge by integrating a physical (P) model (SAHYSMOD) with a group (stakeholder) built system dynamics model (GBSDM) through a component modeling approach based on widely applied tools such as MS Excel, Python and Visual Basic for Applications (VBA). The coupled model (P-GBSDM) was applied to test soil salinity management scenarios (proposed by stakeholders) for the Haveli region of the Rechna Doab Basin in Pakistan. Scenarios such as on-farm water storage, vertical drainage, canal lining and allocation of irrigation water were simulated with the integrated model. Spatial and temporal maps together with performance indicators and economic and environmental trade-off criteria were used to examine the effectiveness of the selected management scenarios. Canal lining was found to be a long-term policy that requires an initial investment from the government. The government sponsored Salinity Control and Reclamation Project (SCARP) appears to be a short-term policy that resulted in a considerable increase in water availability and farmer income through assured groundwater supplies but had detrimental effects on soil salinity in the long term. The new P-GBSDM proved to be an effective platform for engaging stakeholders and simulating their proposed management policies while taking into account socioeconomic considerations. This was not possible using the physically based SAHYSMOD model alone.

Keywords: Soil Salinity, Integrated model, Stakeholder, Socio-economics, Watershed, SAHYSMOD, System Dynamics

6.1 Introduction

Simulation models are considered an important tool for developing new policies and technologies, and evaluating their impacts on physical processes and environmental systems. However, many simulation models focus on simulating a single physical process (e.g. hydrological models such as SWAT and MIKE SHE simulate watershed hydrology only (Arnold *et al.* 2012; Hughes and Liu, 2008)) and do not constitute balanced representations of the physical, social and economic components of a system. Land and water resource management policies impact not only physical processes, but also many closely intertwined economic and social processes. This situation often leads to complicated research and management questions, which require the use of integrated models for appropriate assessment. These models must be developed with dynamic feedbacks between socio-economic and physical components to simulate a holistic system response. Integrated model simulations may also be helpful in providing management solutions by highlighting congruous policies for sustainable agriculture, where economic policy decisions, farmer responses, and cropping patterns depend on results from physical processes and where changes in physical processes are due to socio-economic conditions and the interacting processes of all stakeholders. This form of dynamic model integration remains a challenge due to the inherent differences between socio-economic and physical models, such as programming languages, conceptual frameworks, computation procedures, spatial and temporal resolutions, and human-environment heterogeneity (Marohn *et al.* 2013).

Many studies have tried to address this challenge by combining different process components using integrated modeling approaches such as OpenMI (Open Model Integration Environment), scripting by writing model codes in Java, C++, and Python, and component modeling or wrapper programming (Bulatewicz *et al.* 2013; Langsdale *et al.* 2006; Melbourne-Thomas *et al.* 2011; Predrag Prodanovic and Simonovic, 2007). OpenMI is an open environment where two OpenMI-compliant models communicate directly, using one file as a go-between. This method requires the least modeling effort; however, it is only effective for OpenMI-compliant models (See (Gijsbers *et al.* 2005) for detailed description). Script programming, also known as the solid set or hardcoded approach, involves translating the models into a single common language and building them as one single application unit. This method requires considerable modeling skill and time. Component models, or wrappers, are a loose coupling approach in which component programs act as a wrapper to make the output of one model compatible as an input for the other model and vice-versa.

Previously developed integrated models (e.g. Laudien *et al.* 2008; Saysel, 2004) based on the above approaches successfully demonstrated the usefulness of model coupling through improved interaction between system components. However, such integrated models were developed without stakeholders' participation. A study by *Davies* [2008] represents the special case of a socioecological system in which stakeholders' actions were explicitly incorporated into environmental processes by defining social demands and growth exogenously, i.e. outside system boundaries. Although that study employed user built scenarios (e.g. wastewater treatment, land-use, carbon tax etc.) to test different policies.

Only a few model coupling studies, such as one done by *Prodanovic and Simonovic* [2007], incorporate the dynamic interactions between social, physical, and environmental processes. They dynamically coupled HEC-HMS with a system dynamics model (using a scripting approach) by modifying the source code of both the models in Java and analyzing the impacts of climate change on the Upper Thames watershed in southwestern Ontario, Canada. This study illustrates the benefits of coupling a socio-economic system dynamics model with a well-tested expert simulation model of physical processes. However, this coupling approach has limited applicability due to the great amount of effort and skill required. Particularly in the case of participatory-built system dynamics models (one component of the present study), this methodology has significant limitations largely due to the uniqueness of the group model. The central model attributes of the participatory model (e.g. variables included, time steps) depend on the choices of the stakeholders group, and the exchange variables (i.e. variables that exist in both models) between the models might therefore repeatedly change during the participatory modelling process. This situation demands a general, transparent, and flexible coupling approach that can be applied with a standardized model (such as, for example, a soil salinity model) to simulate the entire socio-economic and physical system. However, such a model coupling approach does not exist at the moment. This paper focuses on addressing this literature gap through development of a novel model coupling approach. The approach is based on commonly available, easily manageable, and transparent modeling tools easily understood even by non-modelers. The following section summarizes the methods, strengths, and weaknesses of previous studies on the subject of integrated soil salinity modeling.

6.2 Integrated Models of Soil Salinity

With the advancement of computer simulation tools model coupling has become the focus of researchers aiming to integrate the strengths of the many existing models. According to *Liu et al.* [2008], due to the multi-disciplinary nature of problems, the applicability of a single computational "super-model" is neither feasible nor desirable. Rather, broad all-encompassing macroscale models should be built by linking different microscale models to represent a holistic view of knowledge regarding the system. *Saysel and Barlas* [2001], for instance, developed an integrated system in a dynamic modeling environment; the system was developed through the integration of four physical processes involved in root zone salinization: irrigation, drainage, groundwater discharge, and groundwater intrusion. They employed the solid set or hardcoded approach by translating micro component process models into the system dynamics environment. Finally, the regional scale model developed via this process was applied to a comprehensive environmental analysis in a semiarid region of Turkey. They developed their model in a flexible modeling environment, increasing model applicability in other studies. However, the model was developed through the translation of expert physical models and failed to represent stakeholders' views and policy options.

In another study, *Laudien et al.* [2008] developed an integrated modeling tool for evaluating the impact of water exploitation on groundwater and soil salinity changes. They successfully applied this integrated model in West Africa to the problem of efficient management of water resources with consideration of the salt buildup process. The comprehensive model linked four existing microscale models of groundwater, irrigation water demand, domestic water demand, and soil salinity using ArcGIS. Model modules were loosely coupled by following a component modeling or wrapper programming approach. Building models using a modular approach allows the user to maintain their implemented module or model equations. However, this integrated system was developed without any socio-economic components.

Some studies tried to address this limitation by translating process-based models into the system dynamics modeling environment. For example, *Nozari and Liaghat* [2014] developed a system dynamics model with the main focus of estimating drainage water quality and quantity and the subsequent effect of drainage effluent on soil salinity. Their model was based on sub-models of water balance, salt balance, and the convention-dispersion equation. They used a solid set approach in which various model components were linked together to form one unit. A number of past modeling studies tried to link different biophysical system components through feedbacks (Fernández and Selma, 2004; Li and Simonovic, 2002; Smith *et al.* 2005; Stave, 2003). These models closely mimic their real-world equivalents. However, integrated models have not been widely accepted by stakeholders due to limited participation of end users and the use of complex modeling tools they are not familiar with (Prodanovic and Simonovic, 2010).

None of the above integrated models attempted to include stakeholders' perceptions and socio-economic issues in the soil salinity modeling process. The coupling of expert models (in this case physical models) and system dynamics models (in this case stakeholder built socio-economic models) requires a transparent and flexible coupling approach that can be applied via participatory processes. The present paper focuses on the development of such an approach through the coupling of a participatory-built system dynamics model with the physical Spatial Agro Hydro Soil Salinity Model (SAHYSMOD). In the coupled model (P-GBSDM), the physical soil salinity model (SAHYSMOD) simulates the movement of salts and water within the crop root zone, transition zone, and aquifer, whereas the participatory-built system dynamics model is used for simulating socio-economic aspects and stakeholders' preferred policy scenarios. The proposed methodology is based on the component modeling approach, where a widely-applied tool, MS Excel, is used as a wrapper to exchange information between the socioeconomic and physical systems. To the best of the authors' knowledge, no study linking a distributed soil salinity model with a participatory-built system dynamics model currently exists in the literature.

The remaining sections of this paper are structured as follows. Section 6.3 provides a detailed description of coupled model (P-GBSDM) components. After describing the details of the interchanging variables in Section 6.3.3, the details of the proposed coupling approach for the transparent and flexible linking of the expert model and the system dynamics model are presented in Section 6.3.4. This is followed by a scenario development for soil salinity management in Rechna Doab Pakistan in Section 6.5. Scenario spatial analysis is presented in section 6.6. Section 6.7 provides details of economic and environmental trade-off evaluations. Section 6.8 describes strengths of the P-GBSDM in comparison to SAHYSMOD. Finally, the overall conclusions are presented in Section 6.9.

6.3 Materials and Methods

The overall GBSDM model and its structure, equations, and component details are presented in a companion paper *Inam et al.* [2017a], whereas details regarding the physical SAHYSMOD model (P) and its calibration, validation, uncertainty, and sensitivity analysis are presented in *Inam et al.* [2017a]. The SAHYSMOD model developed in *Inam et al.* [2017b] is the same as the model used in the present study. However, use of the physical model (SAHYSMOD) alone as in *Inam et al.* [2017b] without integration with GBSDM (i.e. exchange of inputs from the socio-economic model, as was not done in *Inam et al.* [2017b]) does not simulate the effects of socio-economic changes on soil salinity. The following section briefly describes both components of P-GBSDM.

6.3.1 GBSDM Description

The first component of the integrated model uses a well-tested methodology called "system dynamics" modelling [*Sterman*, 2000]. Systems dynamics is a graphical user interface-based modeling system that represents real-world behavior through nonlinear feedbacks between system components. System dynamics modeling provides a flexible modeling system for physical as well as social-economic processes with the opportunity to include participants in the model building process (Langsdale *et al.* 2006). System dynamics models have been successfully used for water resources planning, policy analysis, sustainable development, and natural resource management (Dai *et al.* 2012; Hare *et al.* 2003; P Prodanovic and Simonovic, 2007; Sendzimir *et al.* 2007)

In the current study the model's main emphasis was on soil salinity management. The system dynamics part of the overall coupled model was implemented in Vensim DSS, a system dynamics modeling interface environment (Ventana Systems, 2003). Very few system dynamics modeling studies exist on soil salinity management in general [*Saysel and Barla*s, 2001], and existing studies focus mainly on the physical components alone without consideration of socio-economic factors. The current system dynamics modeling study is the first of its kind to use a participatory modeling approach to develop a holistic model consisting of both the physical and socio-economic components of a water resources system.

The systems dynamics model development process consists of two stages. In the first stage, an innovative approach to qualitative modeling based on systems thinking analysis was used which was developed by the authors in a previous study (Inam *et al.* 2015). The proposed approach was used for the 'co-construction' of the participatory model that allows for the direct involvement of stakeholders with limited technical expertise, under conditions of limited financial and time resources. The systems thinking analysis methodology employed was based on the feedback loops of Causal Loop Diagrams (CLDs) to evaluate qualitative system responses through stakeholder participation. The potential stakeholders identified in this study were the Ministry of Agriculture and Livestock, the agricultural industry, an NGO (Punjab Rural Support Programme (PRSP)), research organizations (International Water Management Institute (IWMI), Pakistan Council of Research in Water Resources (PSRWR), Soil Fertility Research Institute (SFRI)), the Ministry of Water and Power (sub-departments of Soil Monitoring Organization (SMO), International Waterlogging and Salinity Research Institute (IWASRI)), the Irrigation Department, Farmers' Organizations (FOs), and the Land Reclamation Department of Pakistan.

In the first stage, sixteen potential stakeholder groups were contacted by the facilitator (the first author of this manuscript) and were asked to build their own CLD on a sheet of paper. The facilitator visited each stakeholder group in person and helped each stakeholder develop their CLD (the training and building of each CLD lasted approximately 2-3 hours per stakeholder). CLDs proved to be a time effective approach for preparing stakeholder mental map models. Each CLD developed by each stakeholder encapsulated the stakeholder's perceptions (i.e. mental map) regarding the causes, consequences, feedbacks, and solutions to address the problem of soil salinity. Using CLDs, stakeholders proposed various policies with special consideration of economic, social, environmental, and technical details. All stakeholders were in agreement that the soil salinity problem in Rechna Doab is due to the inequitable distribution of surface water supplies, which forces farmers to use marginal quality groundwater to irrigate their crops. In the next step, the facilitator integrated the stakeholder built CLDs to prepare a preliminary group CLD with all elements (including differences reflected in the CLDs of different stakeholders). These elements were then discussed and addressed in a large group meeting (lasting one full day) where all stakeholder groups were brought together to create an overall group CLD. Stakeholders were satisfied with the overall CLD model they had developed, and highlighted the need to adopt this approach for other environmental issues. Finally, the facilitator split the merged/integrated CLD model details into different thematic sub-models and translated the thematic sub-models into Vensim DSS software. The thematic models (i.e. agriculture, water, management, and economic sub-models) were connected to one another, but organized into sub-models to ensure the overall merged model was relatively simple to understand.

In the second stage, the thematic models extracted from the stakeholder-built CLD were quantified in the form of stock and flow models using appropriate modeling equations and assumptions. Stock variables represent the state of the system (e.g. water level of reservoir) controlled through outflows (e.g. water drains) and inflows (e.g. rainfall and irrigation). A "downward approach", as suggested by *Sivapalan et al.* [2003], was followed for quantification. Under this approach key processes were identified on thematic maps and then expanded stepwise to explore the details of system behavior at a watershed scale. Four subsystem modules (agriculture, economics, water and management) of key processes (agricultural water demand and conjunctive use, canal lining and seepage, effective rainfall, surface water storage, groundwater abstraction, irrigation application efficiency, crop yield, and farm income), as identified by stakeholders, were linked together through feedbacks to form a holistic representation of the system. GBSDM process interactions through feedbacks are summarized in Figure 6.1a. The details can be found in the companion paper *Inam et al.* [2017a]. Various management policy levers in the form of switches (0 for off and 1 for on) were incorporated into the quantified model to evaluate the effects of policies individually, as well as in combination.

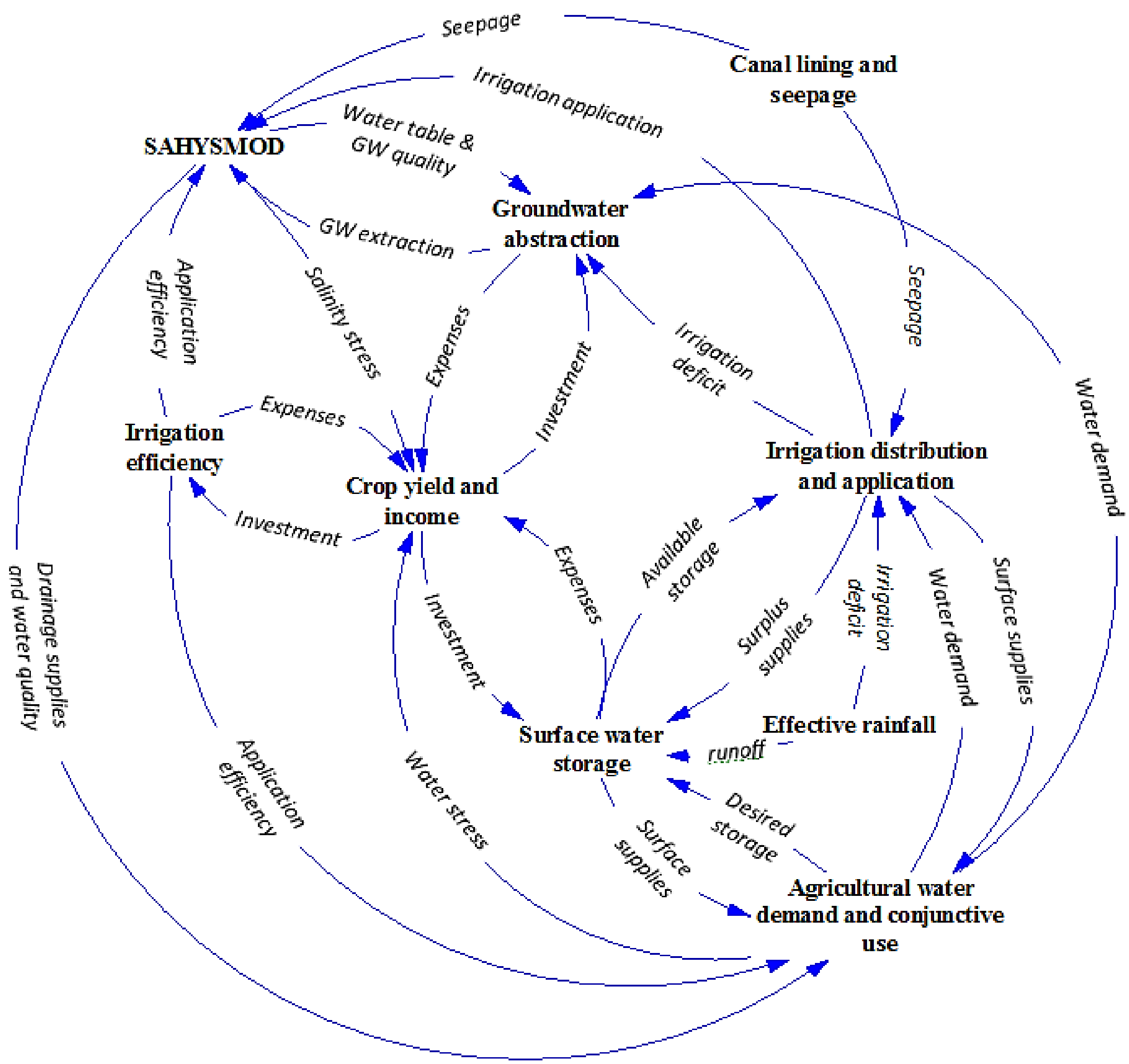


Figure 6.1a. System dynamics model modules and their feedbacks

6.3.2 SAHYSMOD description (the P component of the P-GBSDM model)

A number of physical modeling tools, such as LEACHM, DRAINMOD-S, SALTMOD, SWAP, HYDRUS, and SAHYSMOD [*Hutson and Wagenet*, 1989; *Oosterbaan and de Lima*, 1989; *Kandil et al.* 1995; *Van Dam et al.* 1997] exist and are used in the literature to predict the status of soil salinity under different management scenarios. The latter of these was developed by combining the agro-hydro salinity model SALTMOD with the polygonal groundwater model SGMP (Standard Groundwater Model Package) to create SAHYSMOD to simulate the long-term effect of management practices on soil salinity in the root zone, transition zone, and aquifer.

SAHYSMOD has been successfully applied and tested under arid climatic conditions in various regions of the world (Akram *et al.* 2009; Desta, 2009a; Kaledhonkar and Keshari, 2007; Liaghat and Mashal, 2010; Singh and Panda, 2012b). SAHYSMOD was selected for the physical modeling portion of this study because it contained the majority of the soil salinity processes reported as important by stakeholders in the first phase of the study (see *Inam et al.* [2015] for details). It also provided a wide range of agricultural management options (such as farmer response to soil salinity, the option of horizontal as well as vertical drainage, surface drainage, conjunctive water use, and crop rotation with changes in the soil salinity profile) to allow for the testing of different management scenarios.

SAHYSMOD is written in Delphi with a graphic user interface for the input of seasonal data for the salt and water balance components. The inputted data is used to relate surface water hydrology (e.g. precipitation, evaporation, irrigation, water reuse, and runoff) to groundwater hydrology (e.g. seepage, drainage, pumping). SAHYSMOD operates on a seasonal basis and gives output in terms of actual evaporation, downward percolation, upward capillary rise, subsurface drainage, soil salinity, and groundwater flow [*Oosterbaan*, 1995]. The model provides a wide variety of simulation options by using three kinds of agricultural practices (lightly irrigated, heavily irrigated, and non-irrigated/rain-fed or fallow land) as well as horizontal and vertical drainage, farmer response with crop rotational index, and drainage water reuse. SAHYSMOD divides the soil profile into four layers: surface reservoir, root zone, transition zone, and aquifer; the agricultural water and salt balance is computed for each layer. The model works based on a block-centered finite difference approach for solving the well-known Bousinesque equations. The model divides the whole area into polygons and then calculates average conditions at the centroid of each polygon. Nodal centroid point co-ordinates were used to define the distribution of cropping, irrigation, drainage, and groundwater characteristics over the study area. SAHYSMOD processes and component details are summarized in Figure 6.1b.

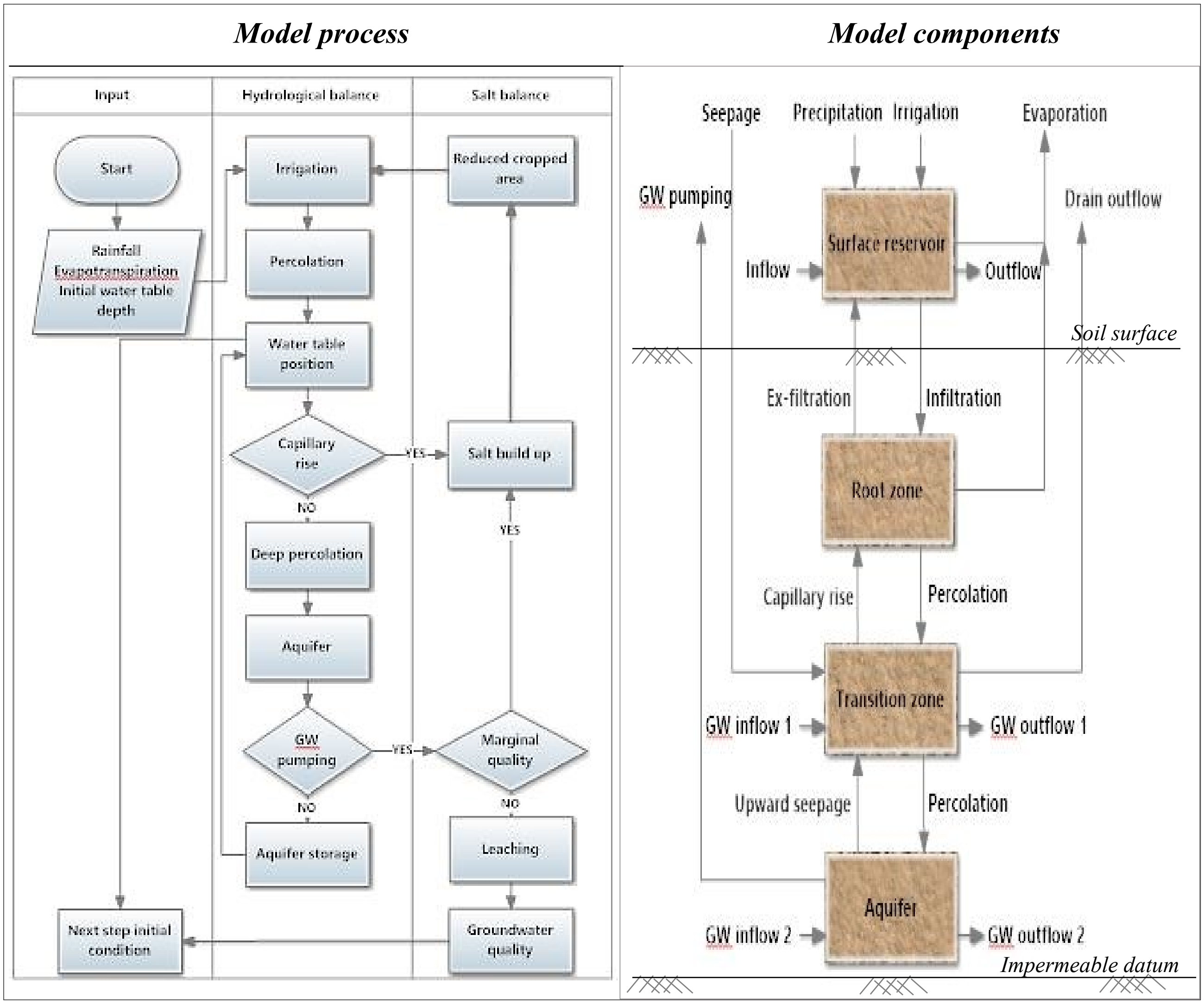


Figure 6.1b. Flowchart of SAHYSMOD model components with hydrological and salt balance simulation processes

In the current modeling study, seasonal periods were defined through site observation. A year was divided into two seasons of six-month durations (i.e. Rabi (winter) from November to March and Kharif (summer) from April to October). The study area was subdivided via a nodal network, and spatial variation in soil salinity was modeled with a series of 279 square polygons (215 internal and 64 external) each 21 × 21 cm in size at a scale of 1:10000. Due to spatial interaction, calibration was a challenging task, as there are many variables and combinations that can potentially play a role. GlueWin (GLUE for Windows) software [*Ratto and Saltelli*, 2004], was used to characterize uncertainty, sensitivity, and parameter estimation for model calibration and validation. One thousand input data files created through Monte Carlo simulations were classified as behavior and non-behavior sets using threshold likelihood values. The model was calibrated (1983-1988) and validated (1998-2003) through satisfactory agreement between simulated and observed data. The data acquisition and technical details of SAHYSMOD are described in a previous paper by the authors *Inam et al.* [2017b]. Details and description of the model interchange variables are summarized in the following section.

6.3.3 Model Interchange Variables

Coupling both model components (i.e. P and GBSDM) through feedbacks captures changes in socio-economic conditions and their effect on physical conditions, thus producing results that more closely mimic real-world situations. Table 6.1 lists the interchanging variables of SAHYSMOD (i.e. P) and Vensim DSS (i.e. GBSDM) with their descriptions and units. Details of the proposed coupling approach employed to transparently and flexibly link the two models are discussed in Section 6.3.4.

Table 6.1. Model interfacing variables and their units

Variables	Units	Description	Interchanging process	SAHYSMOD ↔Vensim
Water table depth	m	Seasonal average depth of water table below soil surface	Exchanged at the end of each season	Dw → Groundwater level
Root zone salinity	dS m^{-1}	Soil salinity in root zone of crop	Exchanged at the end of each season	Cr → Soil Salinity
Water quality	dS m^{-1}	Seasonal average salt concentration of water in the aquifer.	Exchanged at the end of each season	Cqf → Groundwater Quality
Cropped area Area A Area B Area U	 Fraction Fraction Fraction	Percetage of total polygonal area. i.e. *Cultivated + uncultivated = 1*	Summer and winter seasonal area fraction of cultivated and uncultivated land is directly input from SAHYSMOD at the end of each season.	Area → Cropped area
(Vensim input) Summer crops Winter crops Uncultivated area	 Fraction Fraction Fraction			
Seepage	m^3 $season^{-1}$ m^{-2}	Rate of seepage from canal network under lined and unlined option.	Total seepage per unit area from all sources (e.g. rainfall, surface storage, canal) is summed and input to SAHYSMOD at the end of each season.	Lc ← seepage

Irrigation application	m^3 $season^{-1}$ m^{-2}	The rate of canal supplies per polygon	Total irrigation supplies per unit area from all sources (e.g. rainfall, surface storage, canal) is summed up for group A and B type of crops and input to SAHYSMOD at the end of each season.	Ia ← irrigation supplies
Tubewell growth and capacity	m^3 $month^{-1}$ m^{-2}	Groundwater abstraction rate per polygon with Fw = 1 i.e. all the abstracted amount is used to supplement irrigation supplies. This assumption is made because due to high cost of pumping farmers pump water only when there is a need for irrigation. (see *Inam et al.* [2017a] for Fw details)	Total groundwater abstraction rate per unit area is input directly to SAHYSMOD at the end of each season.	Gw ← groundwater abstraction
Application efficiency	Fraction	Ratio of water applied to water stored in root zone	Irrigation efficiency values for group A, B and U at the end of each season is exchanged with SAHYSMOD	Fs ← Irrigation efficiency

* Note: A = lightly irrigated crops; B = heavily irrigated crops; U = Uncultivated area.

Feedbacks between the physical and socio-economic models are shown through a simple causal loop diagram in Figure 6.1c. The left portion of the diagram (Figure 6.1c) describes the details of the SAHYSMOD (P) process through a simple feedback structure, while the right portion presents the socio-economic system dynamics model (GBSDM) with a few selected variables in a simplified form. The coupling of the physical and group-built system dynamics (P-GBSDM) models consist of eight major links (marked with bold lines in Figure 6.1c) that form multiple feedback loops. Due to space limitations, a description of only two of these feedback loops is provided as an example.

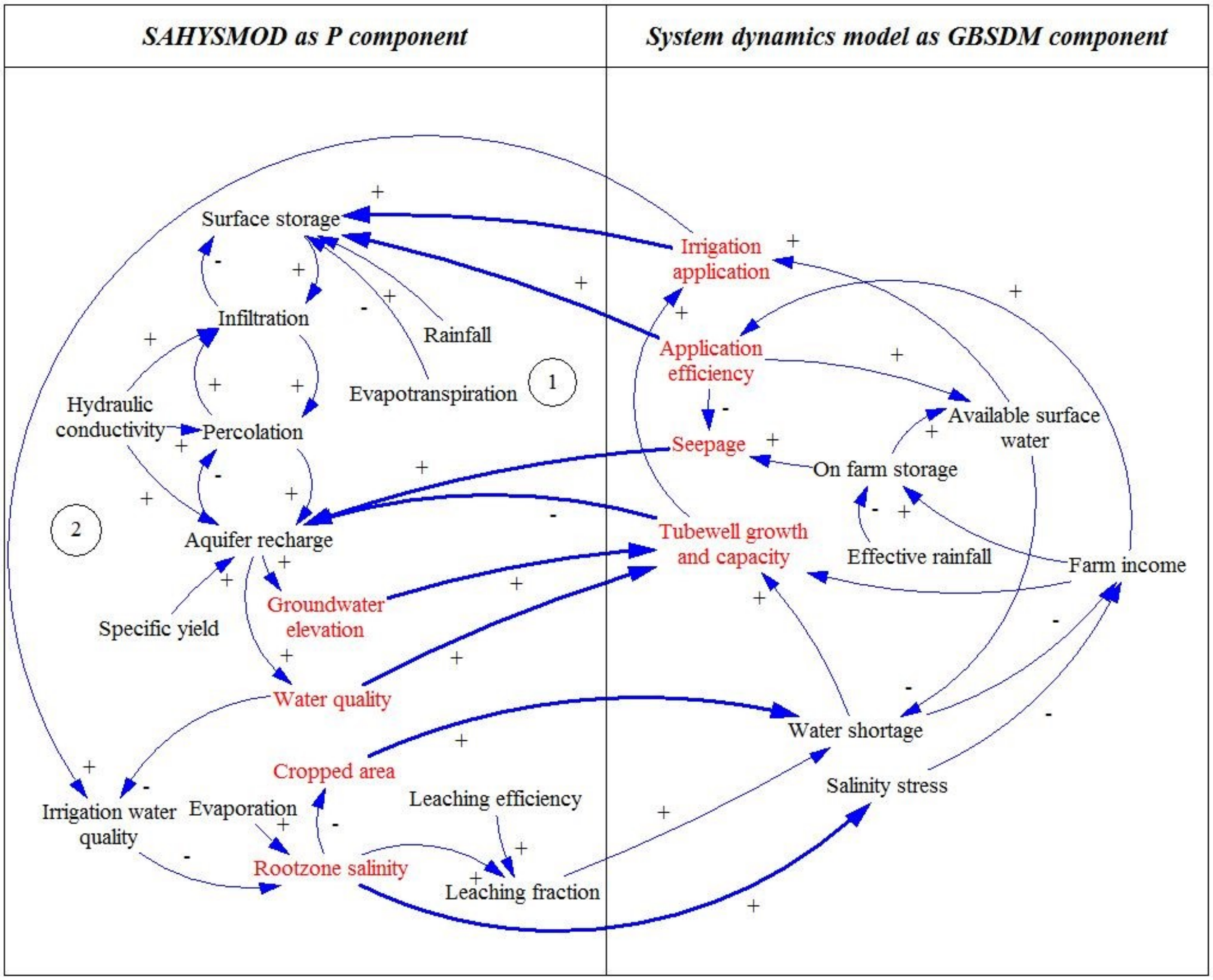


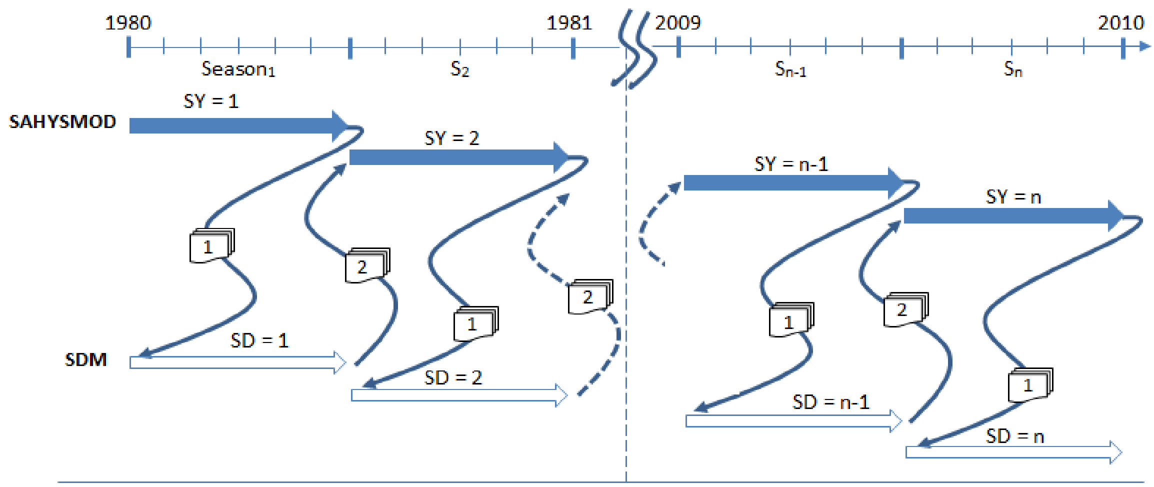
Figure 6.1c. Feedbacks between SAHYSMOD and system dynamics model components. Note: Variables in red = Interchanging variables; Bold arrows = feedbacks between both models

The SAHYSMOD (P) output for water table depth (shown as loop 1) is used as an input in the system dynamics model (GBSDM). A study previously conducted in the region indicated that tubewell operation, maintenance, and installation charges increased exponentially when water table depth dropped below 12 m [*Qureshi et al.* 2003]. The system dynamics model (GBSDM) monitors water table depth and restricts tubewell growth when the water table depth drops below 12 m. This in turn controls the Installation capacity as per expert recommendation (Qureshi *et al.* 2003). Changes in tubewell capacity affect available groundwater supplies for irrigation and thus the amount of water available for irrigation purposes. The system dynamics model (GBSDM) output for irrigation application is updated after each season before being used as an input to SAHYSMOD (P). The physical model calculates infiltration, percolation, and groundwater recharge for the applied volume of water. Water table depth is updated each season based on the feedbacks of the system dynamics simulation model.

The second feedback loop example illustrates how an increase in available monetary resources accelerates the overexploitation of groundwater and affects the sustainability of land resources. An increase in tubewell installation capacity increases the contributions of groundwater supplies and affects the irrigation water quality. SAHYSMOD (P) simulates the effect of conjunctive water use (secondary salinization) and returns predictions of changes in root zone salinity. The status of soil salinity is then updated in the system dynamics model (GBSDM) and a new value for crop yield is calculated based on the updated soil salinity. Next, the updated crop yield is used to estimate farmer income. The system dynamics model (GBSDM) then installs more tubewells only if farmers have enough financial resources to do so. The average installation cost of diesel and tractor-operated tubewells is about 500 US dollars (around 52000 Pakistani rupess) [*Qureshi et al.* 2003]. Any decrease in the farmers' potential to install and operate tubewells decreases the contribution of groundwater supplies to irrigation and vice versa. Other important feedback loops evaluate the effects of improved irrigation efficiency on aquifer recharge, of on-farm water storage on soil salinity as well as on aquifer recharge, and of groundwater quality on tubewell growth.

6.3.4 Model Coupling Approach

Currently existing modeling studies (Fernández and Selma, 2004; Li and Simonovic, 2002; Patrick Smith *et al.* 2005; Prodanovic and Simonovic, 2010; Stave, 2003) that deal with the interaction of the socio-economic components and physical processes of a system have received little attention by end users. This is likely due to the complexity of the integration process as well as the limited involvement of stakeholders in the model-building process. However, integrated models can be more effective and adaptable if built with stakeholders' participation, using a transparent model coupling approach through more easily manageable and less labor intensive modeling tools. In this study, Visual Basic for Application (VBA) built in MS Excel was used as a wrapper to link SAHYSMOD with Vensim DSS (Ventana systems Inc.) (a graphical user interface-based system dynamics modeling environment). For complete coupling, three processes were programmed in VBA: (i) preparation of input files, (ii) import of input data and export of outputs, and (iii) interchange of exchange variables with model execution. The sequence, procedure, and tools used in the model coupling are shown in Figure 6.2.



<u>Exchange procedure 1 (SAHYSMOD ➔SDM)</u>

1. Execute Python script for creating SAHYSMOD input file.
2. Execute SAHYSMOD (Using SahysModConsole.exe through batch file)
3. Processed and import SAHYSMOD output in MS Excel (MS Excel VBA)
4. Copy SAHYSMOD output data variables given in Table 1 to SDM model input file. (MS Excel VBA)

<u>Exchange procedure 2 (SDM ➔SAHYSMOD)</u>

1. Execute Vensim DLL to import SDM input data in Vensim environment.
2. Execute SDM (using Vensim DLL (command option))
3. Processed and import Vensim output in MS Excel (Vensim DLL)
4. Copy Vensim output data variables given in Table 1 to SAHYSMOD model .csv file (MS Excel VBA)

Figure 6.2. Sequence and procedure of data exchange between SAHYSMOD and the system dynamics model (SDM)

At the start of the simulation, data such as surface and groundwater hydrology, soil properties, and socio-economic components are assigned as initial conditions. Then the physical soil salinity model, SAHYSMOD, is executed, and at the end of the season, water table depth, soil salinity, cropped area, and water quality values are imported into MS Excel and transferred to the system dynamics model as inputs. The system dynamics model intakes these updated values before execution, and then simulates the updated dynamics of the socio-economic conditions of the area. The system dynamics model calculates stock values (water demand, farm income, debt, number of tubewells, irrigation efficiency, available water storage capacity, canal lined length, etc.) through rate variables (evapotranspiration, leaching, seepage, income, expenditure, etc.) and updates the management potential of the study area. Updated management measures interact with physical conditions and help to calculate new values of seepage loss, groundwater extraction, water application, and irrigation efficiency. Next, the system dynamics model output is imported into MS Excel and the values of the interacting variables are updated in the SAHYSMOD (.csv) file.

Python script is executed to create the SAHYSMOD input file with updated data before the execution of SAHYSMOD for the next season. Vensim DSS gaming function was used to pause the system dynamic model while SAHYSMOD was in simulation mode. The period of simulation was selected to span from 1990 to 2010 with 40 simulations run over this period for both the physical and system dynamics models. A loop function written in VBA was used for the repeated execution of these procedures (Figure 6.3).

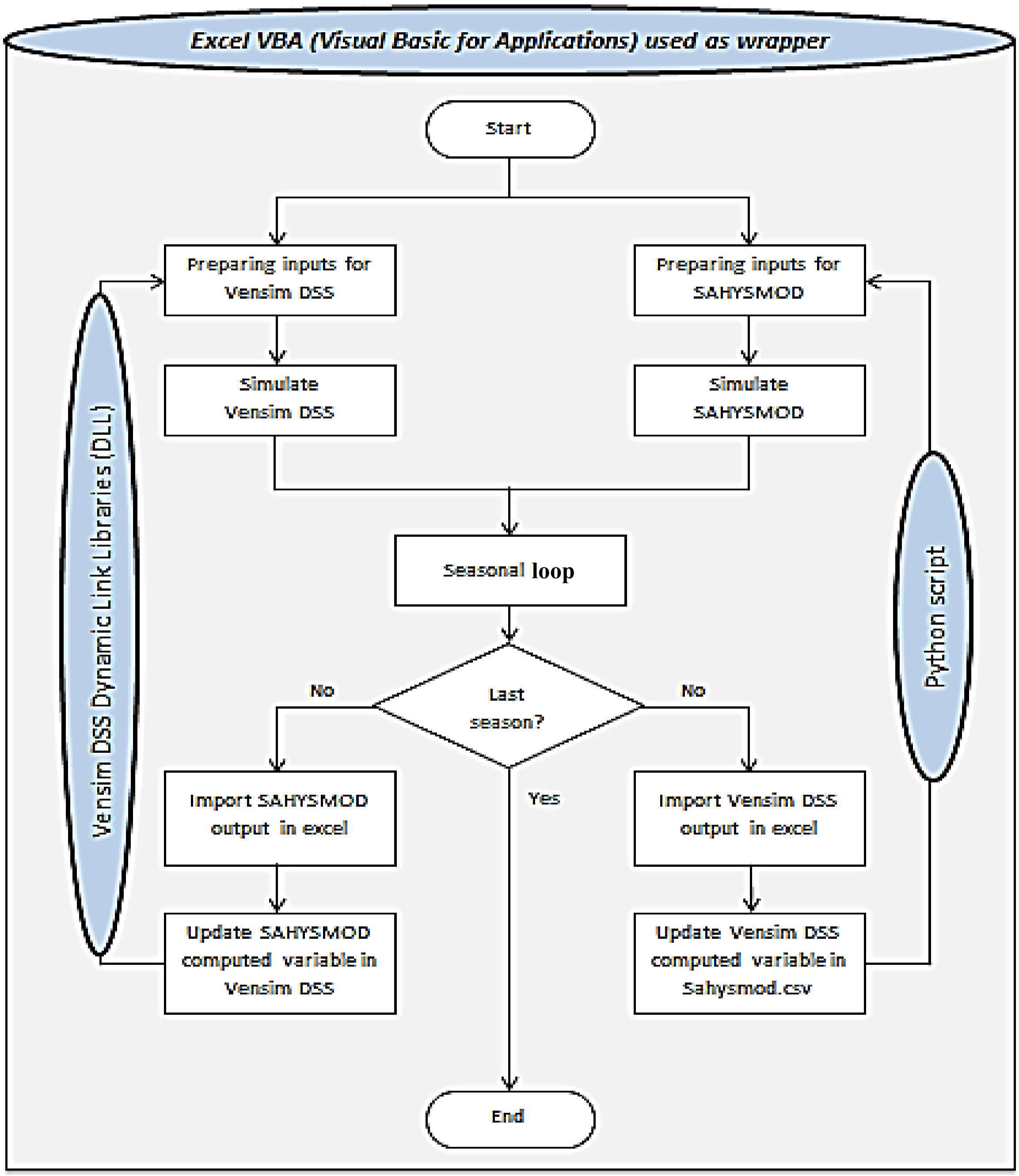


Figure 6.3. Model coupling flowchart with programmed processes. Note: processes with blue background in ovals represent coded tools used for loose model coupling

Both models exchange their outputs on a seasonal time step. A seasonal time step was chosen to predict long-term salinity trends because soil salinization is a slow process that takes three to four seasons to appear on the soil surface. In addition, shorter time steps require much more information, which is not readily available for large areas. The seasonal time step was checked for integration errors using structural validity tests for the system dynamics model and was found to be within the acceptable limits (see *Inam et al.* [2017a] for details). A short description of the model components' interactions is presented as follows.

6.4 Study Area

The coupled model (P-GBSDM) was applied for testing soil salinity management scenarios on a sub-watershed located in the Rechna Doab, Pakistan. The study area lies between 30° 32' N and 31° 08' N latitude and 72° 14' E and 71° 49' E longitude, and covers about 732.50 km^2. It is located just above the confluence of the Ravi and Chenab Rivers and lies within the Haveli Canal command area. Potentially cultivatable land, presently unexploited due to high soil salinity levels, makes up 30% of the area. Groundwater depth varies from 3-6 m, with groundwater electrolyte concentrations exceeding 1500 ppm in the middle portion of the basin [*IWSRI*, 2005]. The details of the study area, along with collected data and data analysis, are provided in a previous paper *Inam et al.* [2017b].

6.5 Scenario Development

Scenarios are important to evaluate the effects of different policy options in terms of possible outcomes and associated benefits. Scenarios can be helpful in three ways: 1) to help policy makers by evaluating a range of possible uncertainties; 2) to highlight emerging issues of importance for the future; 3) to optimize alternative policies. The present study mainly focuses on the third objective. A previously implemented policy known as SCARP (Salinity Control and Reclamation Project) was simulated in the present study to evaluate integrated model performance. In addition, scenarios recommended by stakeholders, such as canal lining, water banking in terms of surface water storage, equal water distribution on canal command, and reallocation of irrigation supplies, as well as several other scenarios, can be simulated using the P-GBSDM. However, in the present study only the stakeholder-recommended scenarios were examined and evaluated for their impacts on water availability, soil salinity, and farm income (i.e. canal lining, canal water reallocation, water banking etc.). Economic analysis of each scenario in relation to a base case scenario was carried out to select the most appropriate scenario on the basis of environmental and economic trade-offs. The following sections discuss the development of alternative scenarios, their descriptions, and their differences with respect to the base scenario.

6.5.1 Base Case Scenario or Business as Usual Case

The base case scenario defines the existing conditions of the watershed, establishing a baseline for investigating and comparing the effects of potential alternative management options. Past seasonal observed data for various parameters, such as canal water supplies, rainfall, groundwater extraction, evapotranspiration, cropping pattern, government subsidies, average crop yields, and crop market value, were acquired from different organizations (Soil Monitoring Organization (SMO), International Water Management Institute (IWMI), Water and Power Development Authority (WAPDA), Punjab Irrigation Department (PID), Pakistan Meteorological Department (PMD), Punjab Agriculture Department (PAD), Statistical Bureau of Pakistan) and input into the P-GBSDM model. The year 1990 was used as the base year. The model was run for 20 years from 1990-2010 (20 years/40 seasons) to establish a business as usual time series.

Alternative management scenarios were developed by making one or more changes in the base case conditions of water availability, tubewell capacity, and inclusion of management options such as canal lining and water banking. The following section describes the formulation of the alternative management scenarios.

6.5.2 Management Scenarios

In this study, the main goal was to test stakeholder-recommended scenarios identified during the stakeholder interview phase of the study (Inam *et al.* 2015) for system sustainability. In addition to stakeholders' suggested options one past implemented policy, SCARP for vertical drainage, was also tested to evaluate model performance. Each option was evaluated for economic and environmental trade-offs (see section 6.7) to identify the best suitable management option in order to achieve the greatest possible long and short-term environmental and socio-economic benefits. Out of several possible promising scenarios, such as conjunctive water use, changes in the cropping pattern, irrigation efficiency improvement through advanced irrigation methods, groundwater extraction control for aquifer sustainability, and limiting tubewell growth according to water quality and groundwater depth and their interactions, only those scenarios preferred by stakeholders were considered for detailed analysis.

Scenarios were selected with the goal of improving surface water supplies in downstream areas, which are typically strongly saline areas, in order to evaluate the effects of surface water availability for minimizing soil salinity and maximizing farm income. This was also in line with stakeholders' recommendations that the area could be reclaimed if good quality irrigation water was made available (Inam *et al.* 2015). Each scenario evaluated the consequence of a series of decisions and provides recommendations as to what policies should be adopted and which should be avoided. Table 6.2 summarizes the formulation of the tested scenarios and specifies the changes involved from the base case scenario. The tested scenarios are summarized below:

- **Base Case (BC)**: Baseline scenario indicating effects of current management practices and used to establish a baseline time series against which to evaluate the effects of the other scenarios. The BC scenario was simulated without any management options selected and using observed data sets only.

- **Canal Lining (S_1)**: The canal lining policy was evaluated due to the following reasons:

  - During the first phase of the study (Inam *et al.* 2015) government officials as well as experts praised the government policy of canal lining, while local farmers criticized the policy in terms of groundwater sustainability. Stakeholders were interested in judging this policy effect on groundwater recharge. Hence this scenario was adopted as per their recommendation and its effect was evaluated in terms of groundwater drawdown (see Figure 6.10).
  - The canal lining policy was also used to test model performance (i.e. is the model simulating the anticipated results (reality check))
  - The economic and environmental trade-offs of the canal lining scenario are estimated. Canal lining requires a considerable amount of financial resources and must be properly evaluated for specific long and short-term outcomes. Economic and environmental trade-offs are not possible with conventional modeling techniques.

- **Canal Water Distribution**: During the first phase of the study (Inam *et al.* 2015), local farmers complained strongly about the inequitable distribution of canal water; they believed that the downstream area could be reclaimed if good quality canal water was made available. A canal water distribution scenario was simulated to analyze the effect of water reallocation on soil salinity changes. This scenario is further subdivided by water distribution strategy:

- **Equal Water Distribution (S_2)**: The irrigation water distribution switch in the base case is disabled, which creates a uniform water distribution over the head, middle, and tail reaches of the irrigation canal.
- **Reallocation of Irrigation Water (S_3)**: During the stakeholder interview phase of the study (Inam *et al.* 2015), the farmer's organization complained about the overdraft of irrigation supplies by upstream farmers. In order to evaluate the effect of controlling the distribution of water, the water distribution factor was redefined in the base case scenario by decreasing the percentage of water allocated to upstream farms and increasing the percentage for downstream users.

- **Water Banking (S_4)**: This scenario was created to examine the effect of on-farm water storage on soil salinity. This scenario was simulated by enabling the surface water storage switch (see Table 6.2). In this scenario, a water banking option allowed for the storage of any excess supplies of irrigation and rainfall water in surface storage ponds and released it according to irrigation needs.
- **SCARP (S_5):** The main purpose of simulating the SCARP scenario was to evaluate the integrated model's performance. SCARP was a vertical drainage policy implemented in the past for salinity control but later discontinued due to insufficient benefits and high costs. The SCARP policy was simulated by increasing tubewell capacity, installation, and maintenance cost in the base case scenario.

Table 6.2. Tested scenarios and the changes involved from the base case.

Main scenarios	Sub-scenarios	Sym-bol	Rain water harvesting switch		Canal lining switch		Irrigation water dist.		Irrigation dist. graphical function	Increase in tubewell capacity	Increase in tubewell cost
			ON	OFF	ON	OFF	ON	OFF			
Base case	-	BC		*		*	*				
Canal lining	-	S_1		*	*		*				
Canal water distribution	Equal	S_2		*		*		*			
	Reallocation	S_3		*		*	*		*		
Water banking	-	S_4	*			*	*				
SCARP	-	S_5		*		*	*			*	*

6.5.3 Scenario Assessment Indicators

As per the scope of this study, each scenario tested was evaluated for soil salinity reduction, water availability, and farm income. Generally, assessment indices are evaluated as the ratio of economic and agronomic variables to unit area (Rs ha^{-1} or kg ha^{-1}), or economic and agronomic variables to unit volume of water applied (Rs m^{-3} or kg m^{-3}), or economic and agronomic variables to unit depth of water applied (Rs m^{-1} or kg m^{-1}). As shown in the following equation:

$$Assessment\ \ Indice = \frac{Agronomic\ \ or\ \ economic\ \ variable}{Area\ \ or\ \ Volume\ \ or\ \ depth} \tag{6.1}$$

P-GBSDM is a distributed model, hence, its indices serve additional benefits (e.g. spatial evaluation of tested scenarios) and can be used to evaluate the effect of scenarios on a canal command basis (e.g. prioritize canal improvements in five-year financial plans of development work) as well as at upstream and downstream locations. P-GBSDM allows for the following assessment indicators to be used for analysis of the results:

- Land productivity (kg ha^{-1}) (i.e. crop yield per unit area)
- Water productivity (kg ML^{-1} and kg mm^{-1}) (i.e. crop yield per unit volume or depth of water applied)
- Land economic indices (Rs ha^{-1}) (i.e. economic return per unit area)
- Water economic indices (Rs ML^{-1} or Rs mm^{-1}) (i.e. economic return per unit volume or depth of water applied)
- Water availability indicator (ML ha^{-1}) (i.e. water available per unit area)
- Water use efficiency indicator (%) (i.e. ratio of water applied to water lost)

However, for the simple and concise representation of scenario results, only two assessment indicators from the above list, one for economic evaluation (Rs ha^{-1}) and the other for water distribution and availability (ML ha^{-1}), were used to understand the trade-offs between the selected scenarios. At the start of each analysis different criteria were defined and the performance of each scenario was assessed based on land productivity, water availability, and economic return.

6.6 Scenario Modelling and Spatial Analysis

Different management options were analyzed with the objective of minimizing soil salinity and maximizing farm income, and water availability. The analysis was performed on the basis of the following research criteria:

- What is the best management option to achieve the required objective?
- Is the selected option economically and environmentally feasible and socially acceptable as per stakeholders' recommendations (Inam *et al.* 2015)?

P-GBSDM produces a large amount of output data, consisting of 130 variables for 40 seasons for 215 polygons for each of the six scenarios. The integrated model output was further filtered to answer the research questions. The analysis of the output was summarized through seven steps. The first three steps described below were used to evaluate the effect of the scenarios on upstream and downstream locations. The remaining four steps, described in Section 6.7, were used to assess the economic and environmental trade-offs between the scenarios.

1. For each polygon, predicted values of farm income, water storage, and water supply (including rainfall, tubewell, and canal supplies) were extracted for each scenario at an interval of 5 years.
2. Water storage and water supply were summed for each polygon to estimate total available water.
3. Scenario maps (Figure 6.4 to 6.6) were prepared in order to evaluate the spatial effect of each scenario.

The base case scenario was simulated using observed datasets (see *Inam et al.* [2017b] for details) without any management measures in order to simulate business as usual. The output maps of the simulated management scenarios described in Table 6.2 are compared with the base case scenario output to evaluate their effects on soil salinity, water availability, and farmer income. Results of the simulated management scenarios are summarized in Figures 6.4 to 6.6.

6.6.1 Soil Salinity

The simulation results for soil salinity are shown in Figure 6.4. The base case scenario shows temporal and spatial variation in root zone soil salinity. High salt concentrations were observed on the downstream side of the canal command area. This was due to a high dependency on marginal quality groundwater due to the lack of availability of good quality irrigation water. Root zone salinity values reached higher than 18 dS m^{-1} in the downstream portion of the canals which is significantly higher than crop tolerance levels of 4 dS m^{-1}. A progressive increase in salt concentration with time indicates that the current agricultural practices are unsustainable and might increase the salt balance in the crop root zone if the same trends continue in the future.

The canal lining scenario (S_1) produced a considerable reduction in root zone salt concentrations both spatially and temporally. After 20 years of simulation a 22% reduction in soil salinity, in comparison to the base case scenario, was observed. The S_1 management scenario's positive impact was due to its control of two main causes of soil salinity, waterlogging and secondary salinization. Increased supplies of canal irrigation water with reduced seepage led to a reduction in soil salinity in the downstream areas of the canal.

The canal water reallocation scenarios (S_2 and S_3) produced a gradual reduction in soil salinity on the watershed scale. Both allocation criteria show similar trends. However, higher reclamation potential was observed under S_3, with a 13% reduction in soil salinity observed after 20 years of simulation. This positive effect was due to the increase in the availability of high-quality water in downstream areas, thereby decreasing the groundwater extraction potential. This in turn helped to control the secondary salinization process.

The water banking scenario (S_4) produced an insignificant effect in comparison to the base case scenario. Similar trends were observed in both cases, with water banking producing a 3% reduction in root zone salt concentration in areas using surplus irrigation water. The similarity of temporal and spatial patterns when compared to conventional practices indicates that the lack of availability of surplus water is mainly due to the region's arid climate.

The SCARP scenario (S_5) produced a considerable spatial and temporal increase in soil salinity over the entire watershed. After 20 years of simulation a 21% increase in the extent of salt effected area was observed in comparison to the base case scenario. Root zone salt concentrations in the downstream area reached higher than 18 dS m^{-1}. The temporal increase in soil salinity indicates the continued use of marginal quality groundwater for irrigated agriculture, which in turn accelerated the process of secondary salinization.

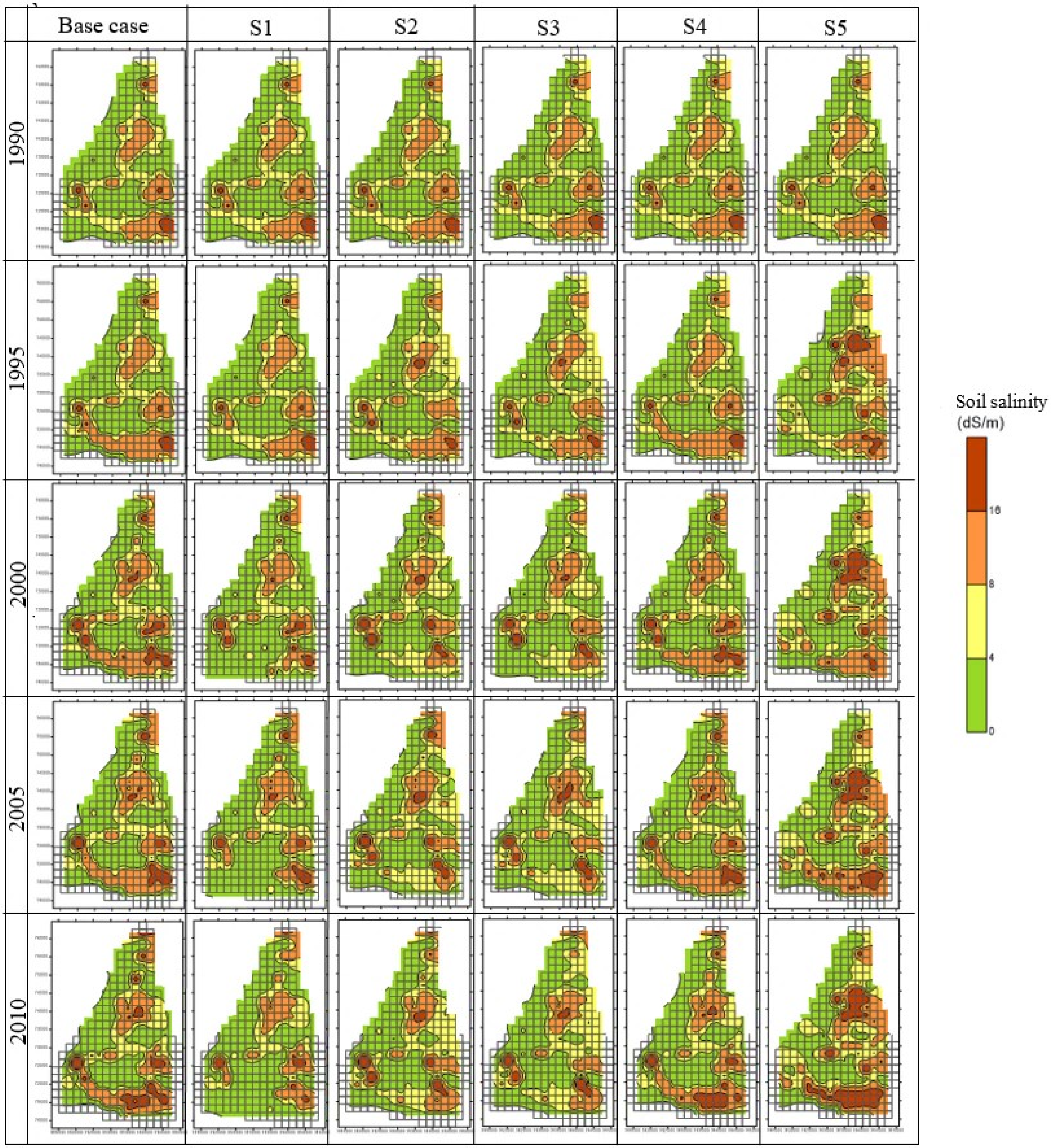


Figure 6.4. Spatial and temporal distribution of soil salinity (dS m^{-1}) under different management scenarios.

6.6.2 Water Availability

Simulation results for water availability are shown in Figure 6.5. A temporal increase in water availability was observed under the base case scenario. This increase was mainly due to the exponential growth of tubewell installation in the watershed (Qureshi *et al.* 2003). Water availability ranged from 7.5-15 ML ha^{-1} upstream compared to 2-7.5 ML ha^{-1} downstream. This difference was mainly due to limited canal supplies and financial resources for groundwater extraction. Temporal analysis illustrates the positive impacts of conventional practices in terms of water availability. However, an increase in root zone salt concentrations denotes an increase in secondary salinization indicating that current agricultural practices are unsustainable.

S_1 showed a temporal increase in water availability over the entire watershed. Water availability ranged from 10-17.5 ML ha^{-1} upstream compared to 5-7.5 ML ha^{-1} downstream. Overall, a 10% increase when compared to the base case scenario was observed after 20 years of simulation. This increase was mainly due to a reduction in seepage losses combined with the exponential growth of tubewell installation.

S_2 and S_3 scenarios indicated a uniform distribution of water over the entire watershed. Water availability was in the range of 7.5-15 ML ha^{-1} upstream compared to 7.5-10 ML ha^{-1} downstream. Compared to the base case scenario no increase was observed in S_2 and a 0.35% increase in water availability was observed in S_3. This indicates that these scenarios were not helpful in increasing water availability but rather helped to better distribute the available resources between upstream and downstream farmers.

The S_4 scenario showed similar trends when compared to the base case scenario. No potential increase in water availability was observed under the water banking approach. This indicates that the water banking policy would not produce significant results if adopted, largely due to the inherent water scarcity in the area. Water availability was in the range of 7.5-15 ML ha^{-1} upstream compared to 2-7.5 ML ha^{-1} downstream. Overall, a 0.80% increase in water availability, as compared to the base case scenario, was observed.

Scenario S_5 produced a considerable increase in water availability over the entire watershed. The increase was mainly due to groundwater extraction from high capacity tubewells. Water availability was in the range of 15-17.5 ML ha^{-1} upstream and 10-15 ML ha^{-1} downstream. Overall, a 50% increase in water availability, as compared to the base case scenario, was observed. The

SCARP project showed positive impacts in terms of water availability but had adverse effects in terms of soil salinity and thus cannot be adopted as a sustainable policy option.

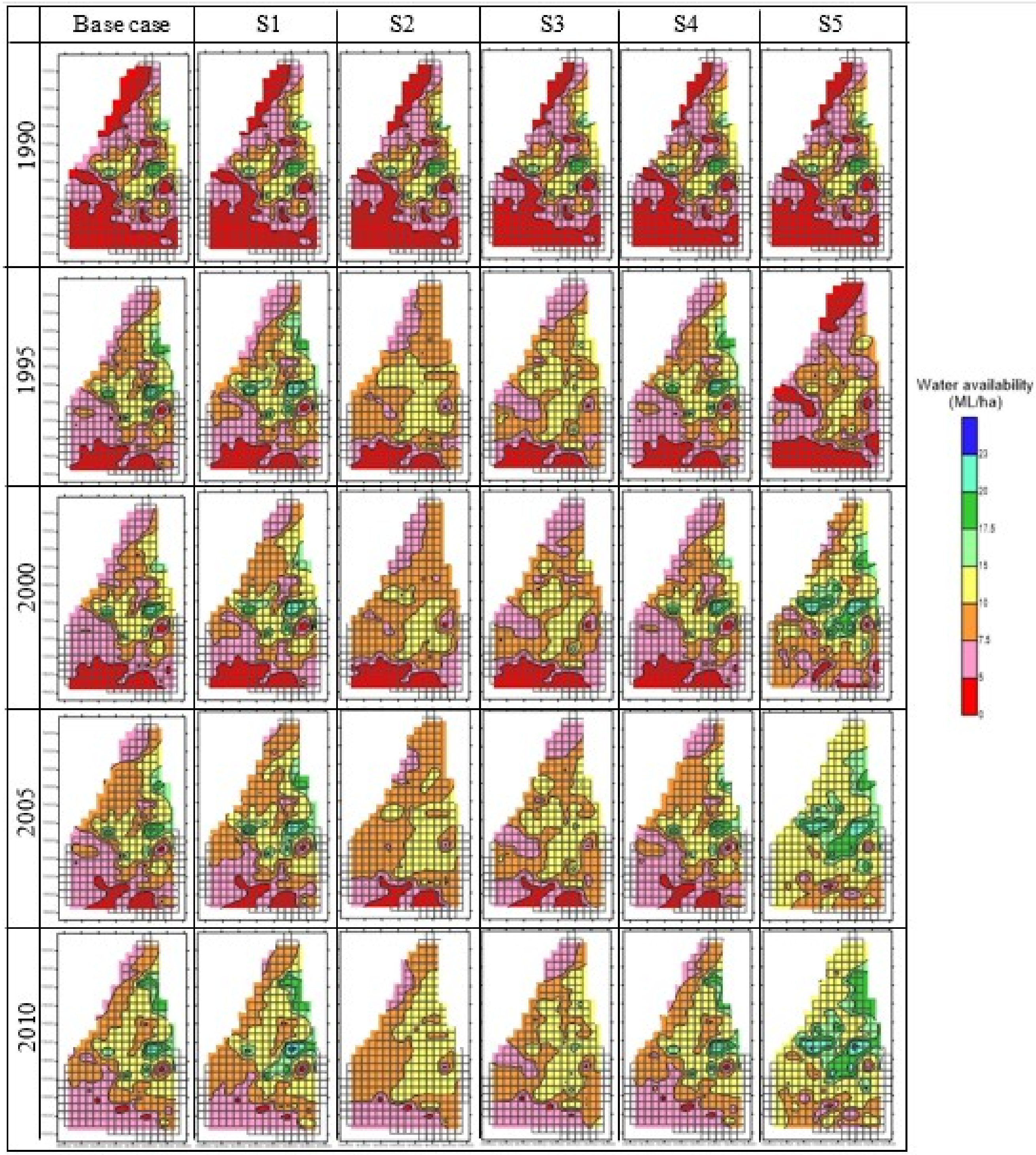


Figure 6.5. Spatial and temporal distribution of water availability (ML ha^{-1}) under different management scenarios.

6.6.3 Farm Income

Simulation results for farm income are shown in Figure 6.6. The base case scenario produced a temporal increase in farm income. This increase was higher in non-saline areas, which varied from 10,000 to 20,000 Rs ha^{-1}, while a reduction of 5000 to 10,000 Rs ha^{-1} in farm income was observed in saline areas. The increase in farm income in non-saline areas can be attributed to supplemental groundwater supplies through accelerated installation of tubewells.

Scenario S_1 produced an increase in farm income. After 20 years of simulation, farm income in non-saline areas ranged from 20,000 to 24,000 Rs ha^{-1}, whereas a reduction of 5000 Rs ha^{-1} was observed in saline areas. The increase was higher in upstream canal areas due to canal water supplies. Overall, a 39% increase in farm income, when compared to the base case scenario, was observed. This considerable increase in farm income can be attributed to an increase in canal water supplies due to reduced seepage losses.

The S_2 and S_3 scenarios resulted in similar patterns in farm income increase. Farm income was around 10,000-20,000 Rs ha^{-1} upstream compared to 0-10,000 Rs ha^{-1} downstream; overall, a 6% increase in incomes in S_2 and a 11% increase in S_3 were observed as compared to the base case scenario. It was observed that agriculture in saline areas is under high stress, with little to no returns. A reduction of 5,000 to 10,000 Rs ha^{-1} over 20 years of simulation was observed in saline areas. This indicates that this policy may not have significant effects in reducing root zone salinity to the level tolerable by crops.

The S_4 scenario shows similar trends when compared to the base case scenario. This indicates that water banking might not be a feasible option due to the scarcity of water mainly attributable to the region’s arid climate. After 20 years of simulation, farm income in non-saline areas varied from 10,000 to 20,000 Rs ha^{-1} whereas a reduction of 5,000 to 10,000 Rs ha^{-1} was observed in saline areas. Overall, a 5% increase in farm income was observed in areas of surplus water.

The S_5 scenario shows a considerable increase in farm income as compared to the base case scenario. This increase is mainly attributable to the increase in water availability through groundwater extraction. After 20 years of simulation, farm income in non-saline areas varied from 10,000 to 20,000 Rs ha^{-1} while in saline areas farm income decreased. A decrease from +10,000

Rs ha^{-1} in the year 2000, to -5000 Rs ha^{-1} in the year 2005, and -20,000 Rs ha^{-1} in the year 2010 was observed. This indicates that this policy is not sustainable in the long-term.

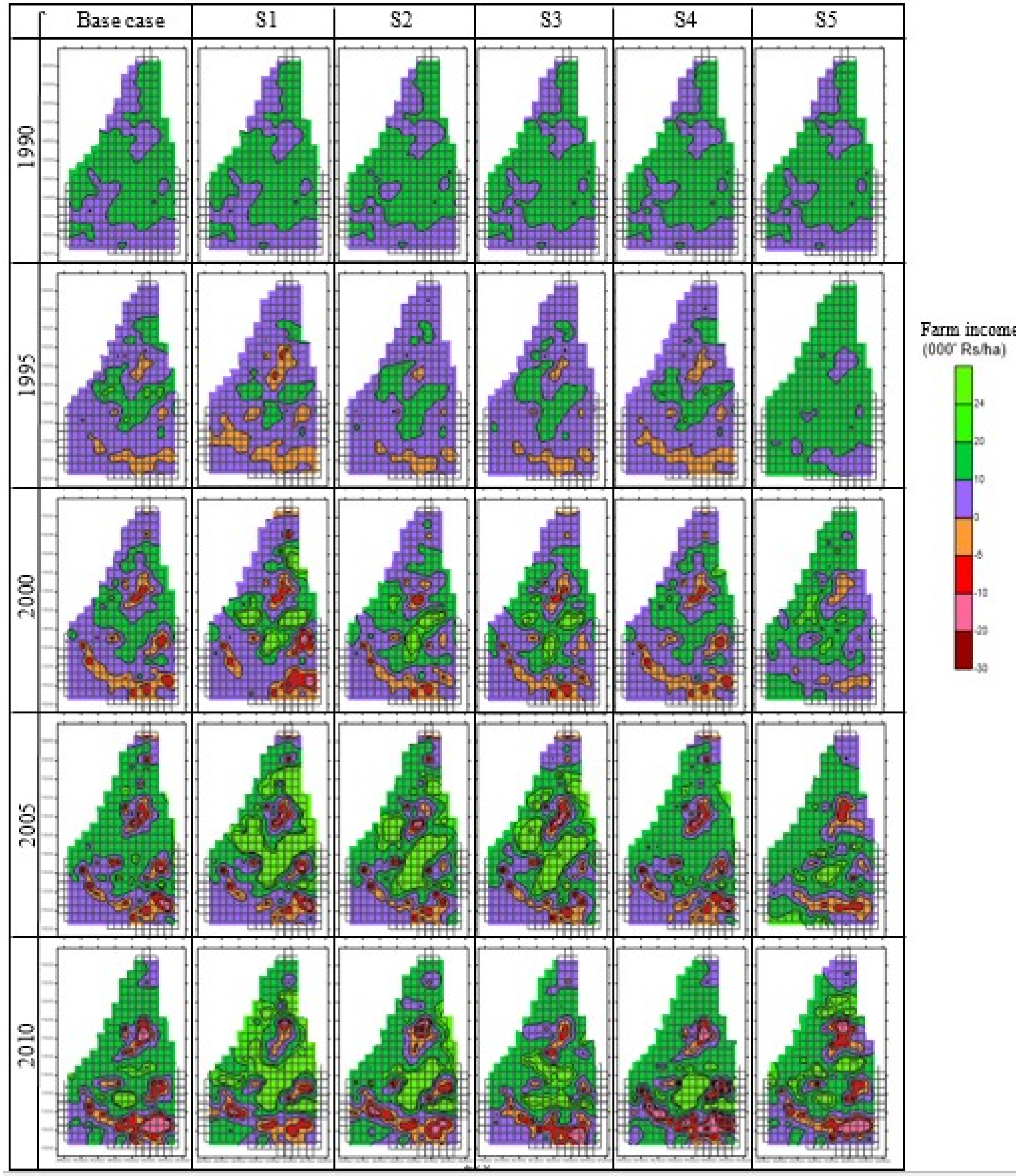


Figure 6.6. Spatial and temporal distribution of farm income (Rs ha^{-1}) under different management scenarios.

The spatial and temporal analysis of the selected management scenarios indicates canal lining is the best suited management option as it produced positive results in terms of decreased root zone soil salinity and increased water availability and farm income. The following section discusses the evaluation of the economic and environmental trade-offs of the selected scenarios.

6.7 Economic and Environmental Trade-off Evaluation

Following the three steps dedicated to the spatial and temporal analysis of the selected scenarios (section 6.6) the next four steps were performed with the aim of evaluating the economic and environmental trade-offs between scenarios.

4. The output of the polygons, computed in the preceding three steps (see section 6.6), for farm income and water availability were summed for each scenario as well as for the base case scenario. These sums represent the lumped farm income and water availability at the watershed scale. The percentage change in farm income in comparison to the base case was estimated using the following equation:

$$Percent\ \ change_{Scenario} = \frac{\sum_{i=1}^{215} farm\ \ income_{scenario} - \sum_{i=1}^{215} farm\ \ income_{BC}}{\sum_{i=1}^{215} farm\ \ income_{BC}} \qquad (6.2)$$

A similar equation is used to estimate percentage change in water availability.

5. The predicted groundwater elevations of the polygons were averaged to estimate total average groundwater elevation over the entire watershed. The percentage drawdown in each scenario in comparison to the base case scenario was computed using the following equation.

$$Drawdown\ \ percentage_{scenario} = \frac{Avg\ \ groundwater\ \ elevation_{scenario} - \ Avg\ \ groundwater\ \ elevation_{BC}}{Avg\ \ groundwater\ \ elevation_{BC}} \qquad (6.3)$$

6. To estimate the percentage change in soil salinity in comparison to the base case scenario, the number of polygons exceeding the non-saline criteria (EC > 4 dS m^{-1}) was counted for each scenario and the percentage change in soil salinity was computed using the following equation.

$$Percentage\ \ change_{scenario} = \frac{Saline\ \ area_{scenario} - Saline\ \ area_{BC}}{Saline\ \ area_{BC}} \qquad (6.4)$$

7. The computed values of percentage change in saline area for each scenario were arranged on a two-dimensional grid of income (x-axis) and performance indicators (see table 6.3) (y-axis) to better understand the trade-offs between the selected scenarios on an economic and environmental basis (see section 6.7.1).

The computed percentages of soil salinity extent, overall water availability, gross agricultural margin, and average water drawdown in comparison to the base case scenario are presented in Table 6.3.

Table 6.3. Percentage changes under management scenarios as compared to the base case scenario

Performance Indicator	Year	Base Case	S_1	S_2	S_3	S_4	S_5
Soil Salinity	1990	0	0	0	0	0	0
	1995	0	-5	-8	-8	-1	13
	2000	0	-23	-19	-14	-5	0
	2005	0	-19	-14	-13	-3	13
	2010	0	-22	-7	-13	0	21
Water Availability	1990	0	0	0	0	0	0
	1995	0	6	-0.66	0.40	0.68	26
	2000	0	10	-0.69	0.13	0.81	57
	2005	0	10	-0.02	0.36	0.83	48
	2010	0	7	-4	-4	0.73	37
Farm Income	1990	0	0	0	0	0	0
	1995	0	-18	4	0.64	-13	93
	2000	0	20	5	6	1.	83
	2005	0	23	9	10	3	29
	2010	0	39	6	11	5	12
Drawdown	1990	0	0	0	0	0	0
	1995	0	0.06	0.1	0.11	0.06	2
	2000	0	0.04	0.09	0.10	0.06	2
	2005	0	0.08	0.13	0.15	0.11	3
	2010	0	0.01	0.11	0.11	0.06	3

A combination of different scenarios might produce better results. However, the main focus of this study was to evaluate integrated model performance and develop a model output analysis procedure. Additional scenarios as well as their combinations will be optimized in a future study, which will help with the identification of the best management scenarios through trade-offs between upstream and downstream farmers on an economic and environmental basis.

6.7.1 Scenario Comparison

The economic evaluation of the tested scenarios was carried out using a 2-dimensional grid and based on the key criteria of economic return and environmental performance. The economic assessment tool used is shown in Figure 6.7. The percentage relative change in farm income in comparison to the base case was plotted on the x-axis, whereas the percentage relative change in environmental performance indicators (soil salinity, groundwater elevation, and water availability) in comparison to the base case were plotted on the y-axis. The analysis was based on the following criteria:

- Is the tested scenario economically and environmentally feasible?

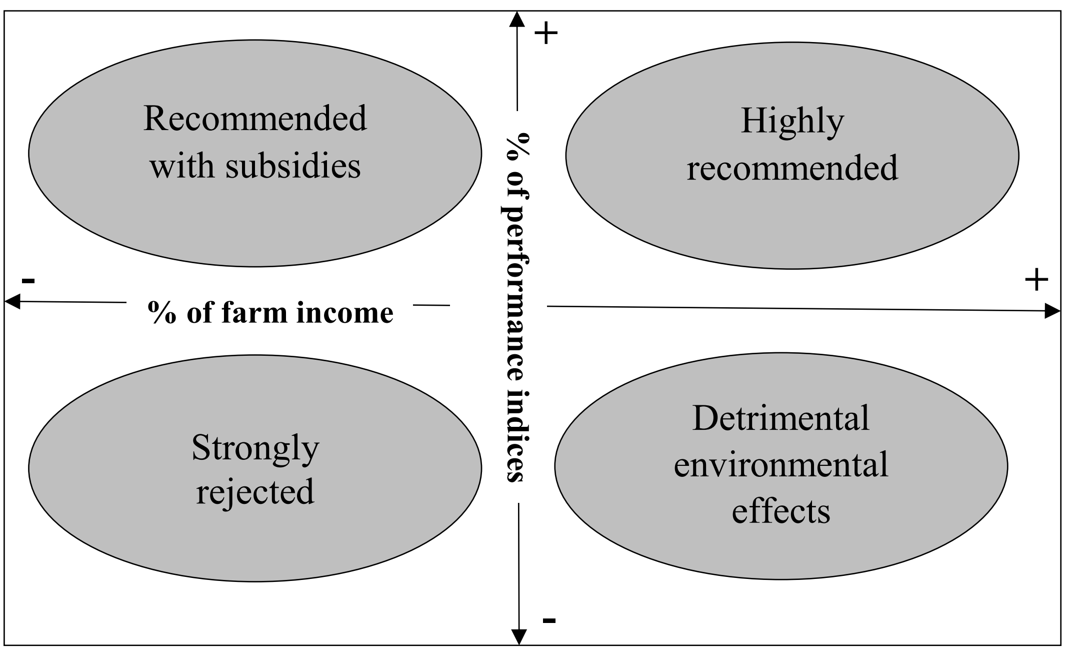


Figure 6.7. Trade-offs between farm income and watershed environmental performance.

The intersection of both axes represents the point of no change or the base case scenario. The upper right corner represents the outcome with the highest returns and a positive environmental impact. Policy outcomes that fall within this section represent highly recommended management options. Outcomes that fall in the lower left corner are neither economically nor environmentally feasible and therefore are strongly rejected due to negative impacts. The top left segment represents outcomes with a positive influence on environmental performance but a negative impact on farm income, therefore highlighting policy options that require government subsidies to implement. Finally, the right bottom segment represents the outcomes with positive economic returns but negative environmental performance. Such policies will result in an increase in agricultural income but at the expense of environmental quality. The economic and environmental trade-offs between the tested scenarios on the basis of different performance indicators are discussed in the following sections.

6.7.1.1 Soil Salinity vs Farm Income

The economic and environmental trade-offs of the tested scenarios on the basis of soil salinity in different time periods are summarized in Figure 6.8. The base case scenario (Business as usual, point 0,0) was used as a threshold and the computed percentages of each management scenario was plotted on the two-dimensional grid. The year 1990 was used as the initial year (not shown here). In 1990 all computed percentages fall at the origin (point 0,0) and thus show similar results to the base case scenario.

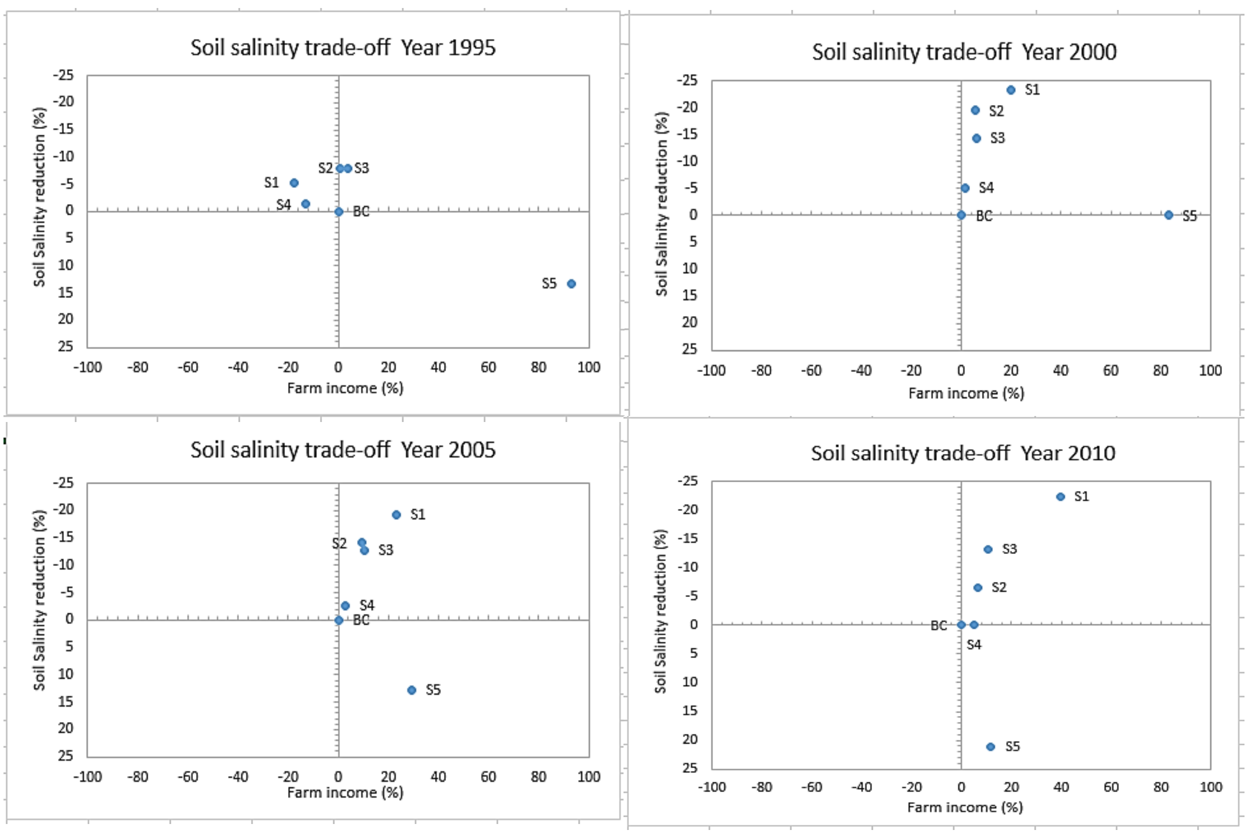


Figure 6.8. Trade-offs between farm income and soil salinity of tested scenarios for different time periods

After five years of simulation (year 1995) both canal lining (S1) and water banking (S4) fall in the upper left corner. This indicates a decrease in soil salinity with an increase in farm income. A reduction of approximately 5% and 1% in soil salinity was observed for the canal lining (S2) and water banking (S4) management scenarios, respectively. However, these management measures require some initial investment, which may result in a reduction in farm income. A reduction in farm income of 18% and 13% was observed for S1 and S4, respectively. These management scenarios require assured government subsidies for their initiation. For the rest of the simulation periods both scenarios (S1 and S4) fall in the upper right corner, which indicates that they decrease soil salinity and increase farm income. Soil salinity reduction was more significant under S1. Reductions in soil salinity of approximately 23%, 19%, and 22% and increases in farm income of 20%, 23%, and 39% were observed in year 2000, year 2005, and year 2010, respectively. Scenario S4 produced insignificant effects with only a 5%, 3%, and 0% soil salinity reduction and a 1%, 3% and 5% improvement in farm income observed for year 2000, year 2005, and year 2010, respectively. This temporal distribution indicates that both scenarios are long-term policies. Both require some initial subsidies from the government but can have positive impacts on a longer terms basis. The less significant effect of the water banking approach indicates that this approach is effective only in upstream areas that have surplus water supplies.

Surface water distribution scenarios, equal water distribution (S2) and reallocation of irrigation water (S3), help reduce soil salinity by 8%. However, an improvement in farm income of only 4% and 1%, respectively, was observed after 5 years of simulation. For the rest of the simulation period both scenarios fell in the upper right corner, which indicates that they help in decreasing soil salinity with an increase in farm income. The S2 scenario (equal water distribution) produced the least significant effect on farm income with a reduction in soil salinity. A reduction in soil salinity of approximately 19%, 14%, and 7% and an increase in farm income of 5%, 9%, and 6% were observed in year 2000, year 2005 and year 2010, respectively. Scenario S3 produced significant effects in the long term with a 14%, 12%, and 13% reduction in soil salinity and a 6%, 10%, and 11% improvement in farm income observed for year 2000, year 2005 and year 2010, respectively. Both scenarios (S2 and S3) helped by increasing canal water supplies in the downstream area thereby reclaiming a significant portion of downstream area and increasing cropping intensity.

For the entire simulation period the SCARP (S5) scenario falls in the bottom right hand quadrant of the two-dimensional grid. This indicates that farm income is more than the base case scenario but at the cost of environmental damage. A gradual decrease in farm income over the time period with an increase in soil salinity was observed. An increase in soil salinity of approximately

0%, 13%, and 21% and an increase in farmer income of 82%, 29%, and 12% were observed for year 2000, year 2005 and year 2010, respectively. The increase in farm income was mainly due to an increase in irrigation water availability attributable to high-capacity tubewells. The initially supplemental supply of irrigation water together with increased cropping intensity compelled farmers to install a large number of tubewells even in areas with marginal quality groundwater. This led to secondary salinization and a gradual decrease in farm income. It was found that the P-GBSDM successfully tested the SCARP policy. The simulated results are in line with the monitoring studies on the SCARP project (i.e. the SCARP schemes supplement irrigation supplies, but degrade normal soils due to the degraded quality of the groundwater) (Jehangir *et al.* 2002; Qureshi *et al.* 2008)

6.7.1.2 Water Availability vs Farm Income

The economic and environmental trade-offs of the scenarios on the basis of water availability at different time intervals are summarized in Figure 6.9. Only canal lining (S1) and SCARP (S5) produced a considerable increase in irrigation water supplies. S1 produced a small increase in availability with a decrease in income during the initial period of canal lining. The decrease in income was mainly attributed to initial investments required for canal lining. An increase in water availability of only 6% and an 18% reduction in farm income were observed. For the rest of the simulation period both scenarios (S1 and S5) fell in the upper right corner, which indicates their positive impact on water availability and farm income. S1 produced an increase in water availability of approximately 10%, 10%, and 7% with a 20%, 23%, and 39% increase in farm income for year 2000, year 2005, and year 2010, respectively, whereas for S5 the increase in water availability was 58%, 48%, and 37% with an 82%, 29%, and 12% increase in farm income over the three time intervals. The gradual decrease in water availability under both scenarios indicates the deterioration of infrastructure and highlights the need for proper maintenance.

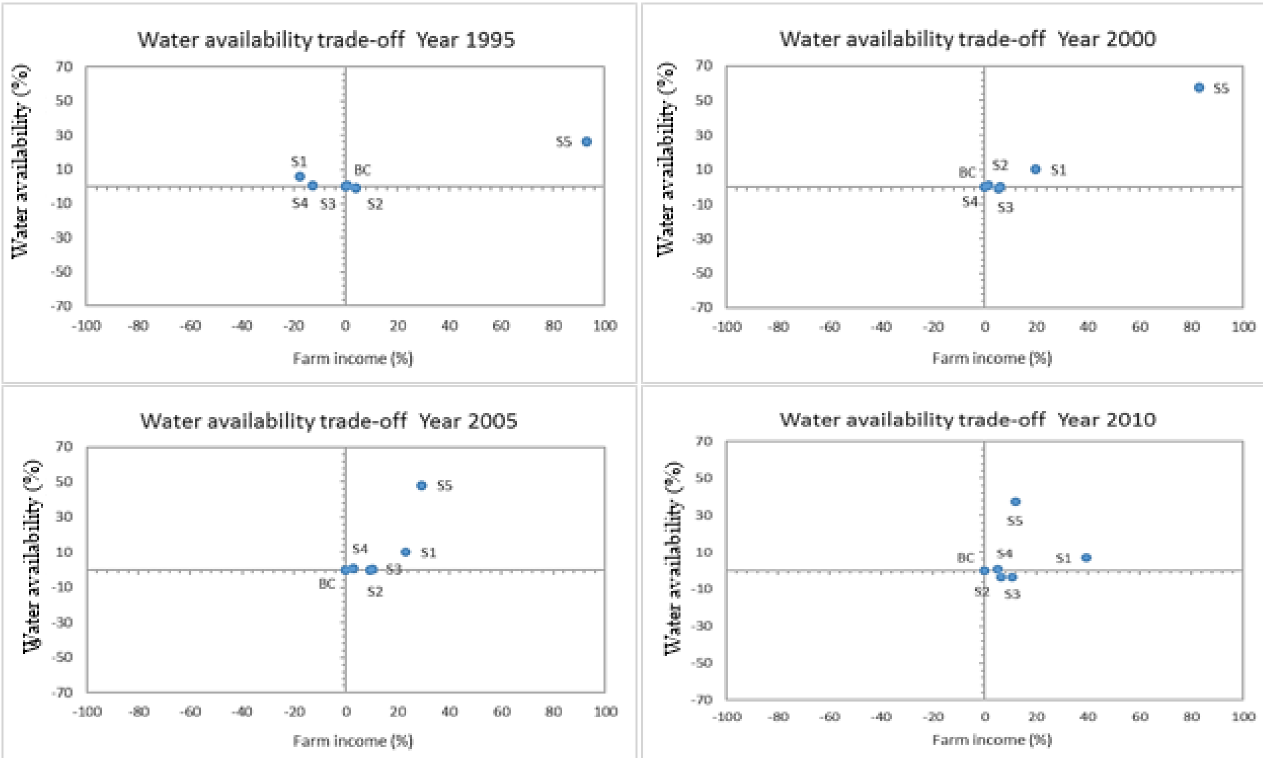


Figure 6.9. Trade-offs between farm income and water availability of the tested scenarios at different time periods

The remaining management scenarios (S2, S3, S4) had insignificant effects in terms of water availability. Insignificant increases in water availability in the range of 0.13% to 0.83% were observed. Scenarios S2 and S3 were based on the reallocation of irrigation water. The insignificant increase in water availability indicates that no additional or saved water enters the system but that, rather, the existing water is redistributed between the upstream and downstream areas. The insignificant increase in water availability in the water banking approach indicates that no surplus water is available in the system mainly due to the arid climate. However, an increase in farm income was observed under each scenario. The increase in farm income was approximately 5%, 9%, and 6 % under S2, 6%, 10%, and 2% under S3, and 1%, 3%, and 5% under S4 for year 2000, year 2005, and year 2010, respectively. The higher increase under scenario S3 indicates that reallocation of irrigation water might help to reclaim downstream areas thereby increasing farm income.

6.7.1.3 Drawdown vs Farm Income

The economic and environmental trade-offs of the tested scenarios on the basis of groundwater drawdown for different time periods are summarized in Figure 6.10. Only SCARP

(S5) produced a considerable effect on groundwater drawdown. S5 falls in the upper right hand quadrant of the two-dimensional grid which indicates the positive impacts of the SCARP policy on groundwater drawdown as well as farm income. S5 produced a change in drawdown of approximately 2%, 2%, 3%, and 3% with a 93%, 83%, 30%, and 12% increase in farm income in year 1995, year 2000, year 2005 and year 2010, respectively. The higher drawdown was mainly due to groundwater extraction from large capacity tubewells. The positive or negative impacts of a larger drawdown on aquifer sustainability in relation to groundwater quality fall outside the scope of this study and thus were not investigated in detail.

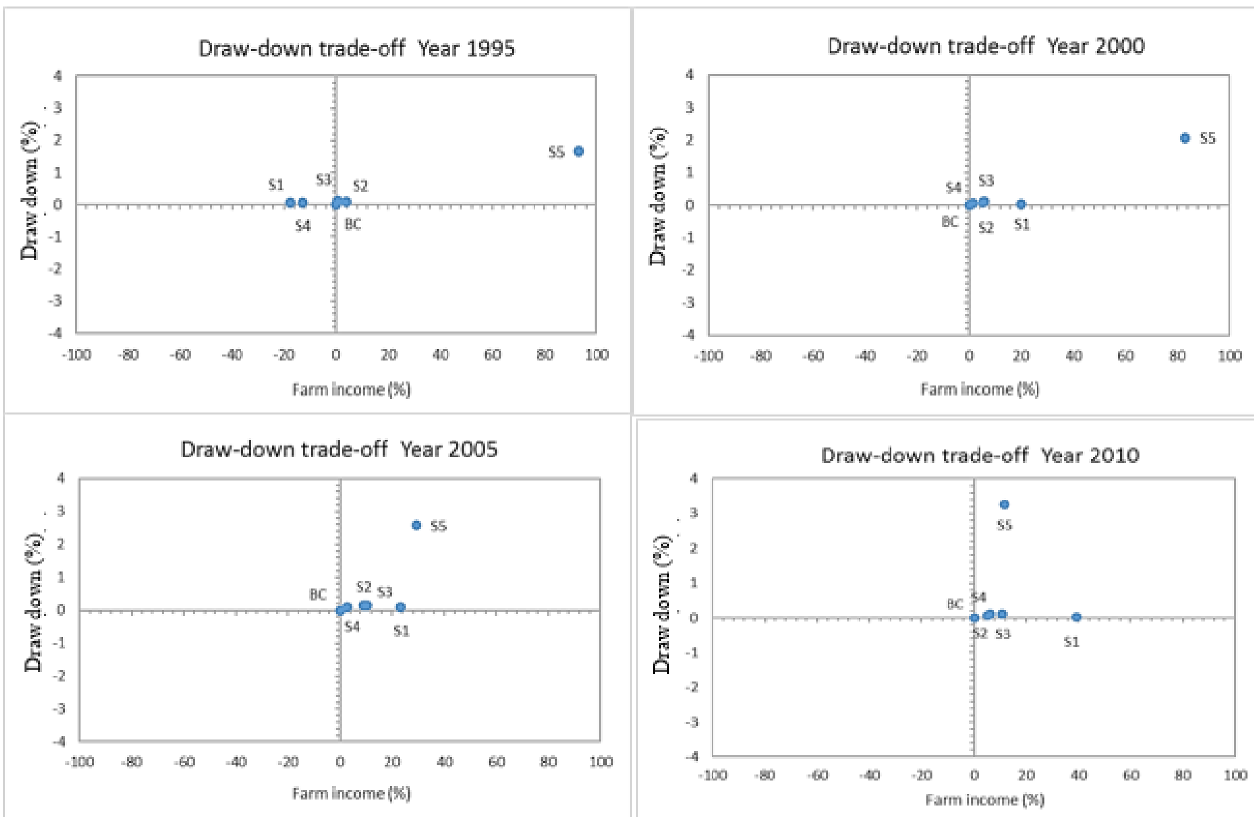


Figure 6.10. Trade-offs between farm income and groundwater drawdown of the tested scenarios at different time periods

The remaining management scenarios (S1, S2, S3, S4) had insignificant effects on groundwater drawdown. The drawdown values under these scenarios varied from 0.02% to 0.15%, which highlights the insignificant effect that these measures had on groundwater changes.

The evaluation of all simulated management scenarios (S1-S5) indicates canal lining is the best management option. Canal lining (S1), though requiring a significant amount of subsidies from the government during its initial stage, may have positive impacts in terms of decreasing soil salinity, increasing water availability, improving farm income, and reducing drawdown for aquifer sustainability. Canal lining can be regarded as a long-term policy, which helps in gradually improving soil salinity and water availability with improved farm income. This finding is opposed to what the local farmer organization believed regarding the canal lining policy and its impact on groundwater recharge (i.e. that it was not useful). However, the canal lining policy results are in line with the views of government officials and research organization experts. A significant increase in crop yield together with farm income was observed under the canal lining scenario. Besides canal lining, another feasible scenario is the reallocation of canal irrigation water. This too can be regarded as a long-term policy; it would have a positive impact in downstream areas in terms of water availability. The results under the reallocation scenario is in line with the views of the local downstream farmers. During the stakeholder interview phase of the study (Inam *et al.* 2015), these farmers strongly emphasized the need to reformulate the guideline to improve water supply in downstream areas. The current study results support their views by indicating an increase in farm income in the downstream area with improved canal water supplies.

The water banking scenario (S4) had insignificant effects with respect to improvement in farm income, water availability and soil salinity reduction. The results are in contrast to stakeholder views regarding the on farm water storage policy. During the first phase of this study (Inam *et al.* 2015), stakeholders were of the view that government subsidies for constructing on-surface storage ponds might have a positive impact. However, the study results suggest it is better to put subsidies in canal lining rather than in surface storage since it will not have any positive impacts due to the scarcity of water which is mainly attributable to the region's arid climate. The SCARP policy results were in agreement with past monitoring studies (Jehangir *et al.* 2002; Qureshi *et al.* 2008). The initial years of simulation suggest SCARP is the best management option. However, though it might have positive impacts, if implemented intermittently, the continued operation of SCARP has the possibility to increase salt concentrations in the crop root zone due to secondary salinization.

The overall framework of the P-GBSDM model provides a unique modeling framework in terms of stakeholder engagement, recording their views and policy options in the form of CLDs, and evaluating their recommended scenarios in terms of environmental and economic trade-offs (in addition to any scenarios deemed potentially useful). The coupled P-GBSDM provides additional capabilities when compared to the physically based SAHYSMOD model. The following section compares P-GBSDM with SAHYSMOD alone in order to highlight the strength and capabilities of the intergraded P-GBSDM model.

6.8 Usefulness of P-GBSDM in comparison with SAHYSMOD

Based on the application of P-GBSDM, it can be seen that soil salinity is a dynamic process that depends on the interactions between water, agronomic, and socio-economic components. These processes are linked through complex, nonlinear, and bidirectional relationships and thus cannot be simulated effectively using physical models such as SAHYSMOD alone. An integrated model such as P-GBSDM can be used to provide recommendations regarding optimum sustainable strategy and policy solutions while taking into account the complexities involved.

The coupled model (P-GBSDM) developed in this study allows for participatory modeling through the inclusion of stakeholders' perceptions, feedbacks between system components, delays, and socio-economic issues in the study area. The P-GBSDM model is capable of performing analyses such as changes in farm income with different cropping patterns under different management practices, spatial prediction of water availability under different management scenarios, effects of soil salinity and water stress on crop yield, growth in groundwater abstraction potentials, on farm water storage and evaluation of economic and environmental trade-offs between different management scenarios, etc. These simulations are not possible using SAHYSMOD alone because of its physical nature. P-GBSDM also helps to address a significant limitation of SAHYSMOD, mainly the use of average meteorological and hydrological data for the entire simulation period. P-GBSDM uses observed time series data for rainfall, evapotranspiration, canal supplies, and cropping patterns, and thus helps to better simulate heterogeneity on a spatial and temporal scale.

6.9 Conclusions

This paper proposes a unique coupling approach for linking a physical model with a participatory-built system dynamics model. The integrated model was applied to assess soil salinity management solutions in the Rechna Doab region of Pakistan. The proposed coupling methodology is based on a component modeling approach where a participatory group built socio-economic model of the study area was developed in a system dynamics modeling environment and then linked with the physical model SAHYSMOD. Both modeling systems use MS Excel as a wrapper and exchange information at seasonal time intervals.

Five modelling scenarios, in addition to a base case scenario, were simulated. The decrease of soil salinity along with the increase of farm income and water availability were used as the evaluation criteria. Three management scenarios (canal lining, water reallocation, and water banking) were selected as per the priorities of stakeholders (Inam *et al.* 2015). SCARP policy was simulated in order to evaluate model performance through a past-implemented policy. Spatial and temporal maps together with performance indicators and economic assessment criteria were used to examine the effectiveness of the selected management scenarios. Canal lining was found to be a long-term policy that requires an initial investment from the government. Under this policy gradual positive impacts, such as soil salinity reduction, water availability improvement, and improved farm income were observed alongside a reduction in drawdown for aquifer sustainability.

Due to the scarcity of water resources in the region, the reallocation of irrigation water and water banking through rainwater harvesting were not found to be feasible options. The integrated model successfully tested the SCARP policy by simulating the results in agreement with past performance monitoring studies on the project (Jehangir *et al.* 2002; Qureshi *et al.* 2008). SCARP appears to be a short-term policy that produced a considerable increase in water availability and farmer income through groundwater supplies but had detrimental effects on soil salinity in the long term. Under this management option, secondary salinization in saline water zones increased, resulting in significant damage to irrigated agriculture. To conclude, the proposed P-GBSDM model can be helpful to policy makers and watershed managers as well as local stakeholders in optimizing alternative management options to ensure a sustainable future.

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CHAPTER 7: **Summary and Conclusions**

The primary focus of this study was to develop an integrated, distributed modeling framework by coupling a Spatial Agro-Hydro-Salinity MODel (SAHYSMOD) with a participatory group built system dynamic model (GBSDM). The model was applied to evaluate soil salinity management scenarios for the Haveli internal canal command area of Rechna Doab, Pakistan. The study area lies between 30° 32’ N and 31° 08’ N latitude and 72° 14’ E and 71° 49’ E longitude and covers about 732 km^2.

Stakeholders of the study area were classified through stakeholder analysis using their roles, power and interest attributes. Potential stakeholders (Ministry of Food, Agriculture and Livestock, agricultural industries, NGOs, research organizations, Ministry of Water and Power, the Irrigation Department, farmer organizations and the Land Reclamation Department) were contacted to prepare qualitative diagrams of their mental maps of soil salinity problems in the form of causal loop diagrams (CLDs). Stakeholder-built CLDs were used to capture local details (e.g. demographic factors, irrigation practices, cropping patterns etc.), socio-economic conditions (poverty level, debt and income, government subsidies etc.) and stakeholder perceptions about future policies. CLDs proved to be an effective approach to address challenges of limited stakeholder expertise, financial resources and time for stakeholder engagement. These constraints are usually considered as main hurdle for engaging stakeholders in developing countries.

Physical processes of CLDs i.e. salt and water movement in crop root zone were modeled with SAHYSMOD. The model was calibrated (1983-1988) and validated (1998-2003) with two five-year periods. The Generalized Likelihood Uncertainty Estimation (GLUE) technique was used for SAHYSMOD calibration, sensitivity and uncertainty analysis. The study area was divided into twelve cluster zones using k-mean techniques. The observed water table depth (WTD) at cluster centroids was compared with the predicted values using NSE, R^2 ME and RMSE statistical methods.

The socio-economic component of CLDs with stakeholder’s preferred policies for soil salinity management was modeled through a methodology called “system dynamics”. A “downward approach” was adopted for developing the GBSDM. The variables were grouped into agriculture, water, economics and management systems. Under each system, distributed submodules using subscripts were developed and linked together through feedback. For example, for the agricultural system, submodules were cropped area fraction, cropping pattern, crop water requirement, net and total water requirements, and conjunctive water use; for the economic system, submodules were crop yield, income and expenditure; for the water system, submodules were effective rainfall, irrigation distribution and application, groundwater abstraction, operation and maintenance cost and net available water; for the management system, submodules were surface water storage, canal lining and seepage, and irrigation efficiency improvement. All submodules were linked together and tested through structural and behavioral validity tests.

Vensim, built in Dynamic Link Libraries (DLL), python, and Visual Basic for Application (VBA), built in MS Excel were used as linking tools to dynamically couple distributed GBSDM with SAHYSMOD. The integrated modeling framework P-GBSDM used MS Excel as wrapper and exchange input and output information on MS Excel worksheets at a seasonal time step. The uniquely developed integrated model took advantage of both modeling systems and helped to simulate socio-economic and physical system interactions with stakeholder inputs.

Management policies recommended by stakeholders such as water banking, irrigation water distribution, and canal lining were simulated through the integrated modeling system. A previously implemented policy (Salinity Control and Reclamation Project (SCARP)) was also simulated to evaluate model performance through anticipated behaviors. The simulated results of scenarios were evaluated using soil salinity, groundwater elevation, water availability and farm income as performance indices. Economic analyses of tested scenarios using economic and environmental returns were carried out to find the best management solution.

The study was divided into four parts (each resulting in a journal manuscript). A summary and conclusion is presented below for each part.

7.1 Stakeholders Engagement for Integrated Model Development Through CLDs

An effective, system thinking methodology based on building qualitative CLDs through stakeholder participation was proposed and applied under constraints of limited time, expertise, and financial resources. Groups of potential stakeholders (i.e. local farmers, experts, government officials, NGOs and agricultural industries) were identified through a stakeholder analysis process based on role, power and interest attributes. Potential stakeholders were invited to build individual CLDs using soil salinity as the main problem variable. The individual CLDs were merged together to represent a holistic view of the system with important aspects such as socio-economic aspects (poverty level, debt and income, government subsidies etc.), demographic details, land use changes, cropping pattern, and preferred management policies for soil salinity. Based on the findings of this study, the following conclusions were drawn:

1. CLDs were found to be an effective and simple method to initialize stakeholder participation to address complex issues. A reinforcing and balancing feedback loop analogy helped to understand the dynamics of the watershed systems through different interacting processes.
2. The CLD provided an excellent platform for group model building that allowed key stakeholders from different organizations and groups to share their views and learn from each other while developing a more thorough and holistic understanding of the watershed system.
3. The inclusion of different sectors rendered the group CLD model a multidimensional approach that provided advantages over traditional uni-dimensional approaches (i.e. physical models).

7.2 Calibration, Sensitivity and Uncertainty Analysis of Physical Component SAHYSMOD

A well developed and tested soil salinity estimation model (SAHYSMOD) was applied to model physical and hydrological processes of the group built CLD. To keep the spatial variation in the soil series and cropping patterns, the study area was divided into a series of 279 rectangular polygons (215 internal and 64 external), each 21 × 21 cm in size (using a scale of 1:10000). An automatic calibration, uncertainty and sensitivity analysis method based on the GLUE technique was developed for SAHYSMOD. The proposed method was based on the Monte Carlo simulation technique. One thousand input data files were created and classified as behaviour and non-behaviour sets using lumped Nash Sutcliffe Efficiency (NSE) (i.e. estimated over the entire watershed using observed and predicted data of all 215 internal polygons) as the threshold likelihood value. A threshold likelihood value of 0.90 was used as the classification criteria. For calibration and validation purposes, the study area was divided into twelve cluster zones using k-mean techniques, and groundwater variations were evaluated at the centroid of each cluster. The model was calibrated (1983-1988) and validated (1998-2003) with two five-year periods using R^2, NSE, ME and RMSE statistical methods. Based on the findings of this study, the following conclusions were drawn:

1. The GLUE methodology worked well for SAHYSMOD and could be used to address data limitation issues. SAHYSMOD gave satisfactory results for the prediction of groundwater elevation when compared with observed data. For model calibration and validation, respectively, R^2 values varied from 0.374-0.816 and 0.498-0.791, NSE values varied from 0.319-0.773 and 0.425-0.735, ME values varied from -0.005-0.213 and -0.038 – 0.504, and RMSE values varied from 0.029 – 0.737 and 0.013 – 1.746.
2. Approximately 70% of the observed groundwater levels fell within the uncertainty bounds. The observed groundwater level for nine of the twelve clusters fell within the uncertainty bounds, which indicated a good approximation of calibrated parameter ranges.
3. Sensitivity analysis identified saturated hydraulic conductivity and groundwater pumping potential as high, and water holding capacity and effective porosity of aquifer, as moderately sensitive variables.

7.3 Development of Stakeholders Built Distributed Socio-Economic-Environmental System Dynamics Model

Socio-economic processes, government subsidies, and stakeholder-suggested policies of the group built CLD were quantified into GBSDM with a widely-accepted system dynamics modeling simulation package, Vensim DSS (Ventana Systems Inc.). GBSDM was classified into agriculture, economics, water and management systems. The submodule of each system was developed and linked with the other system submodules through feedback. The complete model consisted of various stocks (irrigation efficiency, lined length, constructed capacity, silted capacity, water requirement, farm income, debits and tubewell numbers), several rates (seepage, runoff, income, expenditure, decay, construction and water consumption), and look up or table functions (lining rate, water harvesting rate and irrigation efficiency policies, inflation factor, perception states, canal water distribution) to holistically represent the system. The model was subjected to the most recommended validity tests of system dynamic models i.e. structure validity tests (boundary adequacy, structure verification, dimensional consistency, parameter verification, extreme conditions) and behavior validity tests (reality check and evaluating model behavior against the anticipated real conditions). Based on the findings of this study, the following conclusions were drawn:

1. System dynamics has greatest potential for stakeholder engagement and can be used effectively for modeling complex multi-stakeholder environmental issues such as soil salinity.
2. Satisfactory results of structural and behavior validity tests indicated that confidence can be built on formulated structures to simulate different stakeholder proposed management scenarios.

7.4 Coupling and Application of Integrated Distributed Modeling Frame work (P-GBSDM)

SAHYSMOD was coupled with GBSDM to simulate the effect of different policies on groundwater depth and soil salinity changes in the crop root zone. The proposed coupling methodology was based on the component modeling approach where widely applied tools (Vensim, python scripting and VBA for MS Excel) were applied to use MS Excel as wrapper. The model operated on a seasonal time step to exchange information between SAHYSMOD and GBSDM. SCARP, a previously applied vertical drainage policy in the study area was tested with P-GBSDM to evaluate model performance. The newly developed model referred to as P-GBSDM showed great potential to preform simulations of stakeholder proposed scenarios to determine cost effective and collaborative soil salinity management policies. Scenarios such as on-farm water storage, vertical drainage, canal lining and allocation of irrigation water were simulated with the distributed integrated model. Parameters such as groundwater elevation (m), soil salinity (dS m^{-1}), water availability (ML ha^{-1}), and farm income (Rs ha^{-1}) were used as policy assessment indicators. Spatial and temporal maps together with performance indicators and economic and environmental trade-off criteria were used to examine the effectiveness of the selected management scenarios. Based on the findings of this study, the following conclusions were drawn:

1. The coupled P-GBSDM provided additional capabilities when compared to the physically based SAHYSMOD model. The P-GBSDM model was capable of performing analyses such as estimation of farm income, spatial prediction of water availability under different management scenarios, effects of soil salinity and water stress on crop yield, growth in groundwater abstraction potentials, on farm water storage and evaluation of economic and environmental trade-offs between different management scenarios, etc. These simulations are not possible using SAHYSMOD alone

2. The government sponsored SCARP appeared to be a short-term policy that produced a considerable increase in water availability and farmer income through assured groundwater supplies but had detrimental effects on soil salinity in the long term. SCARP helped to increase water availability (+30% of base case) which resulted in a 20% increase in farmer income. However, a 3.7% drawdown in water table levels was observed with a 15 - 20 % increase in soil salinity in the groundwater.
3. The water banking scenario had insignificant effects with respect to improvement in farm income, water availability and soil salinity reduction due to the scarcity of water which is mainly attributable to the arid climate of the region.
4. Reallocation of water availability can be regarded as a long-term policy and would have a positive impact in downstream areas in terms of water availability. Improving water availability downstream helped to reduce soil salinity. Under this scenario, a 4 to 8% reduction in soil salinity with a 9% increase in farm income in the downstream area was observed. However, a 4% reduction in farm income of upstream farmers was also noticed.
5. A significant increase in crop yield together with farm income was observed under the canal lining scenario but it required a significant subsidy from the government during its initial stage. Canal lining improved agricultural productivity by reducing soil salinity by 12% with an 8% improvement in surface water availability. However, during the initial period, a 10% reduction in farm income was observed.

The integrated distributed model (P-GBSDM) developed in this research explicitly combined the strengths of a well-tested agro-hydrological soil salinity physical model (SAHYSMOD) with a group built system dynamics model. The developed model helped in understanding soil salinization processes on a holistic scale using stakeholder perspectives. Furthermore, it will also be helpful in suggesting better policy decisions under conditions of limited resources, highlighting the unforeseen consequences of human-environment interactions, analysing stakeholders' proposed policy options, and designing alternative soil salinity management solutions.

CHAPTER 8: **Contributions to Knowledge and Recommendations for Future Research**

8.1 Contributions to Knowledge

An integrated participatory modeling procedure has been developed that can dynamically simulate human-economic-environment interactions and facilitate the exploration and recommendation of sustainable management solutions related to soil salinity. The main contributions of this dissertation are outlined below.

8.1.1 Methodological

1. A new framework has been developed for coupling physical models with stakeholder-built socioeconomic models to evaluate existing and new policies. The developed framework can help experts, decision makers and stakeholders to dynamically simulate human environment interactions. The framework has been demonstrated by dynamically linking a distributed group-built system dynamics model of socio-economic and environmental dimensions with a physically based model (SAHYSMOD) to evaluate the effects of stakeholder-proposed soil salinity management policies. The distributed group-built system dynamics model is based on qualitative Causal Loop Diagrams (CLDs) that can help to bridge the gap between local stakeholders and policy makers and ensure direct involvement of key stakeholders under conditions of limited time, cost and expertise. The simulated results point to social-economic aspects such as the selection of management measures according to the financial constraints of stakeholders and the effect of government subsidies on soil salinity that have not been considered by other modeling studies to date.

2. A new stepwise procedure for calibration, validation, sensitivity and uncertainty assessment based on the Generalized Likelihood Uncertainty Estimation (GLUE) technique for a distributed soil salinity model (SAHYSMOD) has been developed and applied to address the problem of equifinality. The developed procedure will help in the use of distributed models, like SAHYSMOD, in data-limited environments. Besides calibration, this procedure will also aid in investigating uncertainties in SAHYSMOD results, which have not previously been explored.

8.1.2 Practical

1. The new group-built, coupled, distributed, integrated model increases SAHYSMOD's strength by linking it with a group-built system dynamics model of socio-economic and environmental dimensions. The new model is capable of performing analyses on, for example, changes in farm income with varying cropping patterns under different management practices; spatial prediction of water availability under different management scenarios; effect of growth in tubewell development; effects of on-farm water storage and the evaluation of economic and environmental trade-offs between different management scenarios. These simulations are not possible using SAHYSMOD alone.

8.2 Recommendations for Future Research

1. The simplified quantification of canal water distribution and crop yields needs to be further refined with the integration of additional physical models such as SIC – (Simulation of Irrigation Canals) and DSSAT (Decision Support System for Agro-technology Transfer). The participatory modeling framework should then be linked with spatial mapping software such as ArcGIS or Surfer to produce output directly in the form of policy maps.
2. The simple management policy evaluation procedure based on economic and environmental trade-offs developed in the current research needs to be further refined in order to develop a comprehensive framework. The framework needs to consider the social, economic and environmental uncertainties of the study area and identify best management policies that result in maximum output of objective functions such as water availability, farmer income and soil salinity reduction.
3. Due to the complex nature of the socio-economic- environmental system, simplified model assumptions and unavailability of data, especially for socio-economic components, a detailed uncertainty and sensitivity analysis procedure for the integrated model is needed. This procedure would use the information gained during stakeholder interviews and a comprehensive literature review to assign standard deviations to highly uncertain exogenous model parameters for uncertainty and sensitivity analysis. Such a procedure will help in robust decision-making by addressing the sources of vulnerability.