Troubled waters at the frontier: Mapping access to surface water along an expanding agricultural frontier in the Pilcomayo River Basin

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ABSTRACT

The basin of the Pilcomayo River in the Gran Chaco, an extensive and biodiverse dryland biome in the Southern Cone of South America, is home to many Indigenous peoples and smallholders who rely on access to surface water to support livelihoods such as livestock rearing, fishing, hunting, and honey production. However, in the last two decades, the accelerated expansion of the agricultural commodity frontier has been reducing rural populations’ access to the surface water sources on which their livelihoods depend. The agricultural landholdings that form and drive this expansion reduce rural populations' access to surface water through two main mechanisms: (1) directly enclosing surface water sources within their property bounds, or (2) acting as an effectively impassable boundary along a pathway to surface water. Although there is extensive literature that explores how the process of enclosure limits rural populations’ access to natural resources, surface water is rarely the explicit focus of these studies. This study aims to capture the extent to which the commodity frontier has disrupted rural populations’ access to surface water sources between the years 2000 to 2020, the time frame in which the frontier expanded rapidly. To understand how access to surface water has changed over two decades, I first generated a classification of surface water spatial-temporal stability. This classification captures how often discrete surface water sources have held a certain amount of water, which is important for understanding their capacity to support rural livelihoods. I then used a cost-distance algorithm to quantify how rural populations’ access to these different kinds of surface water has changed annually during the 21-year period. The results reveal that during this time period, the expanding frontier has reduced rural populations’ access to the sources of surface water most likely to hold water at any given time point relative to other sources available. I also found that the disappearance of rural settlements correlates with increasingly limited access to the most spatially-temporally stable surface water sources. These findings indicate that minimal access to spatially-temporally stable surface water sources may reduce the viability of rural populations' livelihoods. Although many rural populations have persisted in the region despite the advance of the frontier, this study’s findings suggest that even these populations face the risk of losing access to important surface water sources if the frontier continues to grow in the rapid, unchecked manner observed in the last two decades.

RÉSUMÉ

Dans le bassin du fleuve Pilcomayo, dans le Gran Chaco, une vaste plaine sèche riche en biodiversité du Cône Sud d'Amérique du Sud, vivent de nombreux peuples indigènes et petits agriculteurs qui dépendent de l'accès à l'eau superficiel pour leur subsistance, comme l'élevage, la pêche, la chasse, et la production de miel. Cependant, au cours des deux dernières décennies, l'expansion accélérée de la frontière agricole a diminué l'accès aux eaux de surface dont les moyens de subsistance ruraux dépendent. Les terres agricoles qui façonnent et alimentent cette expansion réduisent l'accès des populations rurales aux eaux de surface par deux mécanismes principaux : (1) en enfermant directement les masses d'eau dans les limites de leur propriété, ou (2) en agissant comme une frontière effectivement infranchissable le long d'un chemin menant aux masses d'eau. Bien qu'il existe une abondante littérature analysant la manière dont le processus de clôture limite l'accès des populations rurales aux ressources naturelles, l'eau de surface est rarement l'objet explicite de ces études. Cette étude vise à déterminer à quel point la frontière agricole a perturbé l'accès des populations rurales aux masses d'eau entre 2000 et 2020, période au cours de laquelle la frontière s'est rapidement étendue. Pour comprendre comment l'accès à l'eau de surface a changé, j'ai d'abord généré une classification des masses d'eau basée sur le nombre de mois durant lesquels elles contiennent une quantité donnée d'eau. Ceci m'a permis de saisir leur stabilité spatio-temporelle approximative et donc leur capacité de soutenir les populations rurales. J'ai ensuite utilisé un algorithme de coût-distance pour quantifier l'évolution annuelle de l'accès des populations rurales à ces différents types d'eau de surface sur une période de 21 ans. Les résultats révèlent que l'expansion de la frontière a réduit l'accès des populations rurales aux masses d'eau qui présentent une grande stabilité spatio-temporelle par rapport aux autres masses d'eau disponibles. En outre, ils montrent qu'il y a une corrélation entre la disparition des établissements ruraux et la diminution de l'accès. Ces résultats indiquent que la diminution de l'accès aux masses d'eau stables peut réduire la viabilité des moyens de subsistance ruraux. Bien que de nombreuses populations rurales aient persisté dans la région malgré l'avancée de la frontière, les résultats de cette étude suggèrent que même ces populations risquent de perdre l'accès à des masses d'eau importantes si la frontière continue de s'étendre de manière rapide et incontrôlée comme ça a été le cas au cours des deux dernières décennies.

RESUMEN

En la cuenca del río Pilcomayo, en el Gran Chaco, una extensa llanura seca rica en biodiversidad en el Cono Sur de Sudamérica, viven muchos pueblos indígenas y pequeños agricultores que dependen del acceso al agua superficial para sus sustentos, como la cría de ganado, la pesca, la caza, y la producción de miel. Sin embargo, en las dos últimas décadas, la expansión acelerada de la frontera agropecuaria ha ido disminuyendo el acceso de las poblaciones rurales al agua superficial de la que depende su subsistencia. Las tierras agropecuarias que conforman e impulsan esta expansión reducen el acceso de las poblaciones rurales a las aguas superficiales a través de dos mecanismos principales: (1) encerrando directamente los cuerpos de agua dentro de los límites de su propiedad, o (2) actuando como un límite efectivamente infranqueable a lo largo de un camino hacia los cuerpos de agua. Aunque existe abundante literatura que analiza cómo el proceso de cerramiento limita el acceso de las poblaciones rurales a los recursos naturales, el agua superficial rara vez es el objeto explícito de estos estudios. Este estudio pretende captar hasta qué punto la frontera agropecuaria ha perturbado el acceso de las poblaciones rurales a los cuerpos de agua entre los años 2000 y 2020, el periodo de tiempo en el que la frontera se expandió rápidamente. Para entender cómo ha cambiado el acceso al agua superficial, primero generé una clasificación de los cuerpos de agua basada en el número de meses durante que retienen una determinada cantidad de agua. Ésta captó su estabilidad espacio-temporal aproximativa y, por lo tanto, su capacidad de apoyar los sustentos rurales. A continuación, utilicé un algoritmo de coste-distancia para cuantificar cómo ha cambiado anualmente el acceso de las poblaciones rurales a estos diferentes tipos de aguas superficiales durante el periodo de 21 años. Los resultados revelan que la ampliación de la frontera ha reducido el acceso de las poblaciones rurales a los cuerpos de agua con más estabilidad espacio-temporal, en comparación con otros disponibles. Además, muestran que la desaparición de los asentamientos rurales se correlaciona con esta disminución de acceso. Estos resultados indican que la disminución de acceso a cuerpos de agua estables puede disminuir la viabilidad de los sustentos rurales. Aunque muchas poblaciones rurales han persistido en la región a pesar del avance de la frontera, los resultados de este estudio sugieren que incluso éstas corren el riesgo de perder el acceso a importantes cuerpos de agua si la frontera sigue creciendo de la forma rápida y descontrolada observada en las dos últimas décadas.

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CHAPTER 1. INTRODUCTION

Drylands provide a variety of important ecosystem services that have supported unique wildlife as well as diverse human populations that have flourished in these regions throughout history. These biomes are home to around 2 billion people globally (Safriel et al., 2005), possess 35% of the global biodiversity hotspot areas (Davies et al., 2012), and support about half of the world's livestock (FAO, 2019). However, drylands face multiple dire threats, including climate change and unsustainable land/water use and management (FAO, 2019; Buchadas et al. (2022). In the Gran Chaco, one of South America's large dryland biomes, these threats simultaneously shape and are compounded by the ecology, hydrology, and geopolitical climate of the region. The biome is a mosaic of forests, shrublands, grasslands, and wetlands spanning an approximate 800,000 km^2 across four countries: Argentina, Paraguay, Bolivia, and a small portion of Brazil (Iriondo et al., 2000).

Indigenous peoples and other rural smallholders of the Gran Chaco have adapted their versatile subsistence economies and lifestyles to the unique physical geography and ecology of the region (Altrichter 2006; FAO & Fondo Indígena, 2015). However, land use change associated with the expansion of the agricultural commodity frontier and large-scale cattle ranching over the past several decades has resulted in widespread deforestation that disrupts the natural processes of the region (le Polain de Waroux et al., 2018; Fehlenberg et al., 2017). The widespread removal of the region's spatially heterogeneous native vegetation has resulted in changes in evapotranspiration and runoff, which has modified the water balance of affected areas, and, consequently, could alter patterns of surface water distribution (Giménez et al., 2016; Rodríguez et al., 2020). The evolving spatial changes in surface water could further reduce the physical availability to rural populations who practice livelihoods directly or indirectly dependent on surface water. Moreover, the increase in private landholdings for the purposes of commercial commodity-based agriculture and cattle ranching reduces rural populations' access to the natural resources necessary to sustain their livelihoods (Altrichter & Basurto, 2008; Seghezzo et al., 2011). Although this expansion of the agricultural commodity frontier has been taking place for several decades, it accelerated in Argentina, Bolivia, and Paraguay from about the year 2000 onward, in great part due to the global soy boom taking place in the 1990s and into the 2000s (McKay, 2020, p.38; le Polain de Waroux et al., 2018).

1.1. Objectives and research questions

In this thesis, I focus on surface water as a natural resource that rural populations rely on to support their livelihoods. I then assess how rural populations' access to this resource has been changing as a result of the expanding agricultural commodity frontier within the Pilcomayo basin subregion of the Gran Chaco. The analysis spans the years 2000 to 2020 since this 21-year period corresponds to a rapid increase in large-scale agricultural production across the Gran Chaco. The basin of the Pilcomayo River is a large and relatively understudied area in which land use change has been reshaping complex hydrological, social-ecological, and geopolitical interactions at the local, regional, and transnational levels. The river, which originates in Bolivia and serves as the border between Argentina and Paraguay, is a vital source of surface water for the flora and fauna, domestic and wild alike, that rural populations are dependent on. However, rain-fed sources of surface water that are hydrologically disconnected from the river are also important in both directly and indirectly supporting different livelihoods.

The variety of surface water sources in the region leads me to my first research question: *What is the distribution of different types of surface water in the Pilcomayo basin?* Therefore, my first objective was to map the distribution of surface water that rural populations may use to support their livelihoods (e.g., fishing, hunting/gathering, etc.) in the Pilcomayo basin. To do so, I generated a classification scheme based on spatial-temporal variables to identify different types of surface water in the region and map their spatial distribution.

I then sought to understand how rural populations' access to the different types of surface water has been changing as a result of the expanding agricultural commodity frontier, leading to my second research question: *How has rural populations' access to surface water changed with the expansion of the agricultural frontier?* I used annual land cover/use data to determine where the expansion of agriculture (croplands and pasture for ranching), which denote private property and thus limit rural populations' mobility, took place between the years 2000 and 2020. I then quantified the decreasing accessibility of the landscape by calculating the increasing distance between human settlements and surface water sources as areas of expanding agriculture intersect formerly passable corridors of natural land cover within the landscape.

1.2. Thesis outline

I explore the issue of access to surface water in the Pilcomayo basin in six chapters, with the current introduction serving as the first. Chapter 2 explains the conceptual framework that guides my research questions and the interpretation of my results. I constructed the conceptual framework from concepts from sustainable livelihoods, political ecology, socio-hydrology, and hydrosocial theory. For each of these disciplinary focuses, I pay special attention to the ways in which they intersect with the theoretical and empirical observations of access regimes.

In Chapter 3, I outline the regional context of the Pilcomayo basin and the portion of its basin that occurs in the Chaco plains. This chapter explains how the physical geography of the region links to the rural livelihoods and the political-ecological context of the region. The history of agricultural commodity frontier expansion in the Gran Chaco and the dynamics of access to natural resources for rural populations are described at length and connected to the context of the region of the Pilcomayo.

Chapter 4 describes my methodologies. It reviews the procedure that I followed in classifying surface water between the years 2000 and 2020. I applied super non-iterative clustering to monthly surface water detection data created by Pickens et al. (2020) to generate objects representing sources of surface water. Using the same dataset, I then created saturation extent and saturation frequency indices representing the spatial-temporal stability of the objects and applied a size criterion based on surface area as well, resulting in 12 surface water classes into which the objects were categorized. The surface water classes generated served as the inputs for the second analytical component of my study: assessing the changes in rural population's access to surface water in each year starting from 2000 and ending in 2020. I used various human settlement location data sources and land cover/use data from Baumann et al. (2022) to determine the annual change in distance from a settlement to the closest source of surface water of each of the 12 classes.

I present the results of my analysis in Chapter 5. I discuss the spatial distribution of the classes of surface water sources and calculate which surface water classes are the most likely to be encountered within the landscape. I then review findings from the access analysis, which indicate that the most spatially-temporally stable surface water sources are becoming less accessible over time to all human settlements. Settlements that eventually disappeared within the time frame of interest had the least access to these surface water sources in each of the 21 years and also experienced the highest overall decrease in access between 2000 and 2020.

In Chapter 6, I discuss the results from each portion of the analysis and highlight the ways in which the intersection of surface water distribution and the process of frontier expansion impact rural populations' access to surface water capable of supporting their livelihoods. I also review some of the limitations of the classification and the access analysis.

Finally, Chapter 7 provides a comprehensive conclusion in which I summarize the goals of my study and review key findings and insights. I reiterate why the study of surface water access for rural populations in the region of the Pilcomayo is essential in assessing the viability of rural livelihoods that are under threat from the expanding agricultural commodity frontier.

CHAPTER 2. CONCEPTUAL FRAMEWORK

There are several actors (human and non-human) and overlapping processes that must be examined simultaneously in the conceptualisation of surface water as a natural resource that supports livelihoods. Availability of surface water for rural livelihoods is directly defined by the web of interactions between human and nonhuman actors who shape the distribution of different types of surface water and the dimensions of access (FAO, 2019). To capture the constant and simultaneous flow of interactions in this context, my conceptual framework draws from the foundational principles of four bodies of literature: sustainable livelihoods, the theory of access through the lens of political ecology, socio-hydrology, and hydrosocial theory.

2.1. Sustainable livelihoods

The sustainable livelihoods approach aims to facilitate understanding of "the way the poor and vulnerable live their lives" in order to better inform development initiatives intended to help these populations (Serrat, 2017, p.21). Chambers and Conway (1992), key authors in defining *sustainable livelihoods* both as a concept and as a methodological approach, argue that the sustainable livelihoods approach is particularly useful in assessing poverty reduction in rural regions, as rural populations' poverty is outside of the proximal view of the urban centers where powerful political and social institutions are usually concentrated. This feature of sustainable livelihoods makes it particularly applicable to the region in which my research is centered, as the people who directly rely on surface water in the region are rural smallholders and Indigenous populations (I discuss the specific demographic details and various livelihood strategies of these populations in detail in Chapter 3.3).

Chambers and Conway (1992) provided the foundational definition of a sustainable livelihood that has been widely adopted with slight modification over the years. The Department for International Development's (DFID) later formed an updated definition based on Chambers and Conway's original definition:

> "A livelihood comprises the capabilities, assets and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its

> capabilities and assets both now and in the future, while not undermining the natural resource base” (DFID, 1999, p. 1).

The concept of *sustainability* in this definition encompasses both social and environmental sustainability, as illustrated in the last portion of the definition in highlighting the maintenance/enhancement of capabilities and assets without degradation of the natural resources needed to support the livelihood (Krantz, 2001). Nevertheless, these are not mutually exclusive forms of sustainability given the many interconnected variables that can change the conditions of what "sustainable" constitutes in practice. The active and adaptive interactions between human and nonhuman actors greatly influence a livelihood's capacity to avoid "undermining of the natural resource base", as stated in the DFID (2001) definition of a sustainable livelihoods . Therefore, the individuals who practice a given livelihood are not the sole agents who dictate whether a given livelihood is "sustainable". Rather, the sustainability of a livelihood is contingent on the myriad interactions between various actors at different spatial-temporal scales.

In the Gran Chaco in particular, the history of dispossession and marginalisation of rural communities (Cáceres, 2015) and the expansion of the global commodity trade system (le Polain de Waroux et al., 2018) have direct implications for the sustainability of rural livelihoods. The agricultural commodity frontier that feeds the commodity chain necessitates deforestation, causing the direct and indirect degradation of the natural resources that support rural livelihoods (Torella & Adámoli, 2005). As these resources become more scarce and more vulnerable to overexploitation and degradation, tensions and conflict burgeon between the actors driving agricultural expansion and the rural populations (Cáceres, 2015; Torella & Adámoli, 2005), as well as within subsets of the rural populations themselves as the fragmented landscape forces them into closer spatial proximity (Altrichter & Basurto, 2008; Zepharovich et al., 2020). Therefore, the social and ecological impacts of livelihood activities grow "unsustainable" not because of the activities themselves, but because of the broader scale social, economic, political, ecological, and historical processes that have shaped and are actively shaping the current local context.

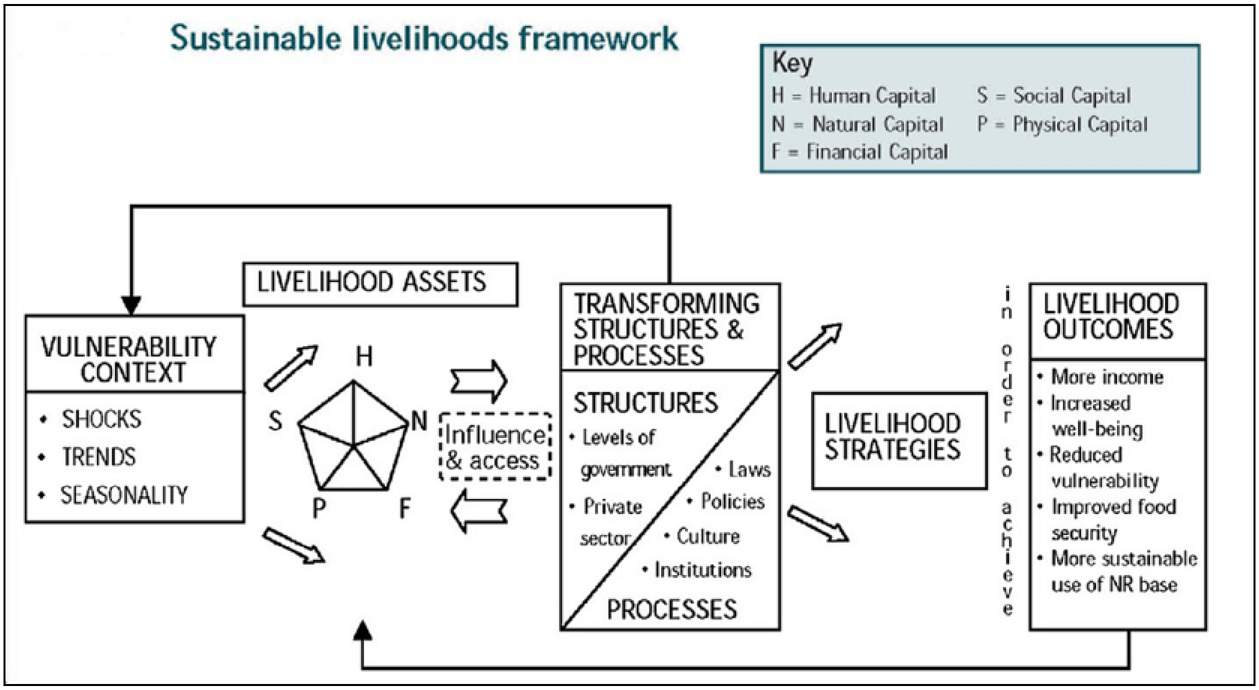

Figure 2.1. DFID (1999) Sustainable livelihoods framework.

According to the DFID definition, a livelihood that is sustainable must also "maintain or enhance its capabilities and assets". According to the Chamber & Conway (1992) definition from which the DFID builds, the term *capabilities* refers to the "proactive and dynamically adaptable" ability to deal with stress and shock and pursue livelihood opportunities (p. 4). Chamber & Conway (1992) place their understanding of *capabilities* within Amartya Sen's framing of the term. Sen (1987) describes *capabilities* as the ability to achieve different subjectively valuable states of being and doing (p. 23-24). Chamber & Conway (1992) posit that within Sen's framing, "there is a subset of livelihood capabilities that include being able to cope with stress and shocks, and being able to find and make use of livelihood opportunities" (p. 4). The DFID framework shown in Figure 2.1 implicitly captures *capabilities* in the interactions between the vulnerability context, access to livelihood assets, and transforming structures and processes.

The *assets* that individuals seek access to are different forms of tangible and intangible capital that serve as reserves, such as food stocks and cash savings, and resources, such as land and farming equipment, to secure the viability of a given livelihood (Chambers & Conway, 1992). A wide array classes and subclasses of capital that can be defined, but many sustainable livelihoods authors (Scoones, 1998; Krantz, 2001; Morse & McNamara, 2013; Serrat, 2017) consider the principal forms of capital as follows: *natural capital* (e.g., water resources, forest products, wildlife, ecosystem services), *physical capital* (human-produced goods and infrastructure such as roads, vehicles, shelter, tools, technology, etc.), *human capital* (good health and nutrition, education, knowledge and skills, capacity to work and adapt, etc.), *social capital* (neighbor-to-neighbor interactions, political representation, leadership, participation in decision-making processes, etc.), and *economic/financial capital* (savings, credit, pensions, wages, etc.).

Turner (2017) explains that some sustainable livelihoods authors believe that *political capital* should be explicitly included as one of the main asset types in the sustainable livelihoods framework. For the purposes of my research, I consider *political capital* to be a key intangible asset to consider. Chambers and Conway (1992) highlight claims and access as forms of intangible assets that can be broadly characterised as *political capital*. The authors define *claims* as the "demands and appeals which can be made for material, moral, or other practical support or access" (p. 8), and *access* as "the opportunity…to use a resource, store, or service or to obtain information, material, technology, employment, food, or income" (p.7-8). Here, *access* is highlighted as an integral asset that enables the obtaining of other intangible assets such as information as well as tangible assets such as stores and resources, all of which maintain and strengthen livelihood capabilities. Though this definition of *access* does not specify *ability*, the term *opportunity* implies a capacity that is effectively congruent to that of ability, as *access* in this context is predicated on a set of circumstances that permit the act of benefitting from a resource to be possible. In any case, all of the forms of capital identified do not exist in isolation of one another, as in many contexts, access itself is negotiated in great part through social institutions and social/cultural identity (Berry, 1992), which are effectively *social capital* in the language of the sustainable livelihoods approach. As such, access to one form of capital can enable and reinforce access to other forms of capital, which facilitates access to other assets that support livelihoods.

2.2. Political ecology and the theory of access

2.2.1. Political ecology

Frank Thone originally coined the term *political ecology* in his 1935 article *Nature ramblings: We fight for grass* (Minch, 2011). Though Thone does not explicitly reference it in the main text, the term is placed just above the title (Thone, 1935). In his article, Thone discusses the tension between Japanese colonists and the Indigenous Mongolian populations, as Japanese colonists' tilling of the land was destroying the native grasslands. He parallels this tension with the conflict between Indigenous North American populations and colonists in the Great Plains of the United States, arguing that the former "fought for grass" because the bison they relied on were dependent on the grassland ecosystem, and the colonists' tilling threatened to completely destroy it. In this first recorded reference to political ecology, Thone presents two real, geographically distinct scenarios that both illustrate an unequal power dynamic between the colonized and the colonizers and result in the colonizers stripping away the colonized's access to resources. Later versions of political ecology would build on the inseparable role of social and political power relations in human-nature interactions.

Eric Wolf brought the term back into circulation in 1972 with his article *Ownership and political ecology* (Minch, 2011). Around this time, development studies and cultural ecology studies were beginning to center political economy as a lens to understand the relations between nature and society. In 1987, Harold Brookfield and Piers Blaikie provided the first "official" definition for political ecology, stating:

> "The phrase 'political ecology' combines the concerns of ecology and a broadly defined political economy. Together this encompasses the constantly shifting dialectic between society and land-based resources, and also within classes and groups within society itself" (2015, p. 17).

Thus, political ecology posits that ecological problems are inherently social and political problems and is explicitly concerned with issues of access and control over resources within the web of power relations (Neumann, 2009; Watts, 2000). In terms of its theoretical framings, political ecology embraces post-structural social theory and the nonequilibrium theory of ecology (Neumann, 2009). Its post-structuralist and nonequilibrium foundations signify that it rejects binaries of truth and knowledge (Woodward et al., 2009), as well as the idea of linear stages of succession in ecosystems (Neumann, 2009). To a certain degree, political ecology's embrace of these theories is also the root of some of the criticisms surrounding the field.

With respect to the critiques of political ecology, there are three main issues that critics identify: (1) a failure to provide practical solutions to the problems outlined, (2) a failure to meaningfully engage with the "ecology" of "political ecology", and (3) a fundamental misunderstanding of the nonequilibrium theory of ecology. According to Peter Walker, himself a political ecologist, "it is possible at times to feel that political ecologists perceive policy as a kind of uncouth distant cousin to be kept at a safe distance" (2006, p. 382), which can stifle the capacity to provide salient recommendations for change. This is reflected in the broader critique of poststructuralism in geography around the 1990s, when "Marxists and some feminists were found accusing post-structuralists of a simplistic idealism and relativist, even nihilist, politics" (Woodward et al., 2009). Furthermore, political ecology sometimes appears to effectively remove the "ecology" element altogether. In these cases, the biophysical ecology and environmental changes that take place may be framed as mere background rather than active agents that shape the context of human struggles (Walker, 2006). Putting the "ecology" so far in the background also generates ample ground to misrepresent ecological theories such as nonequilibrium theory. Some ecologists and environmental scientists have argued that some studies within political ecology have oversimplified humans' roles in ecosystems, leading to the presentation of human-based disturbances as misleadingly positive, "when in reality ecosystems that experience natural flux can also be compromised in ways that weaken their resilience" (Walker, 2006, p. 77).

Despite, or perhaps because of, some of the weaknesses identified with political ecology, the field continues to evolve. Some scholars propose that more explicit engagement with resilience frameworks within socio-nature systems (such as social-ecological systems and socio-hydrology) may improve the field's capacity to offer more concrete, material pathways forward (Ingalls & Stedman, 2016). In my analysis, I borrow approaches from socio-hydrology (discussed in detail later in Section 2.3) to complement the political ecology lens through which I examine access.

2.2.2. Framing access through the lens of political ecology

Watts (2000) argued that the objective of political ecology is: "to understand the complex relations between nature and society through a careful analysis of what one might call the forms of access and control over resources and their implications for environmental health and sustainable livelihoods". This definition explicitly centers access and control of resources as key to understanding the links between the natural environment and society. Ribot and Peluso (2003) define *access* as: "the ability to benefit from things—including material objects, persons, institutions, and symbols" (p. 153). They argue that framing access as an ability, rather than as a right, centers the social and political relationships that restrict or empower resource users to benefit from resources (p. 154). Ability is then centered in relation to power, which manifests as the capacity to affect others' ideas and behaviors; as such, power always emerges from people, even if it is not directly attached to them, such as in the case of an institutional body with disciplining powers (p. 155-156). In other words, Ribot and Peluso's concept of access is fundamentally rooted in contextually implicit and explicit power dynamics and entails all the possible manners in which a person can benefit from a resource (p. 156). Thus, the question of who has access to a resource is entrenched in an intricate web of power relations. Different actors can gain, control, and maintain access in myriad ways across space and time.

Ribot and Peluso (2003) propose the following steps for access analysis: mapping the flow of the particular benefit of interest; identifying the mechanisms that actors employ to gain, control, and maintain the benefit flow and its distribution; and analysing the power relations that enable the application of the mechanisms of access (p.161). The authors identify two primary categories of mechanisms: *rights-based access* and *structural and relational mechanisms of access*. *Rights-based* access can be subdivided into *legal access* and *illegal access*. *Legal access* generally denotes property–that is, the laws or customs define an actor's ability to benefit from a resource–and some form of enforcement to secure the claim to the property. Though one may assume this form of access offers greater security, there is often ambiguity within and between the legal systems that define access, resulting in unclear demarcations of who holds the power to exercise certain rights (p.163). For instance, a national law may conflict directly with a provincial law, and within a local cultural community, customary law may have precedence over state laws; however, even in the aforementioned context, ultimately, the state usually remains the sovereign (p.163). In contrast, *illegal access* refers to "the enjoyment of benefits from things in ways that are not socially sanctioned by state and society…[it] operates through coercion (through force or threat of it) and stealth" (p. 164). As such, "illegal" in this context does not inherently denote "criminal", depending on the actor's relationship with the law and the nature of the law itself. For instance, the owner of a large private landholding that encloses a formerly communal well on the property may have legal rights to access the water from the perspective of the state, but rural community members may not recognize the landowner's rights-based claim to access as legitimate. These community members could argue that they held customary rights to the well prior to the arrival of the new landowner. By this logic, if one of the community members "trespasses" on the property to obtain water "illegally" according to state law, the community members are unlikely to view this as a "criminal" act.

The authors go on to discuss *structural and relational mechanisms* of access, which encompass the political, economic, and social tools that enable an actor to gain, control, or maintain access to additional resources of interest (Ribot & Peluso, 2005, p.164). These mechanisms include technology, capital, markets, labor, knowledge, authority, and social identities and relations. Structural and relational mechanisms of access echo the different forms of *capital* outlined in the sustainable livelihoods framework. However, the key difference in Ribot and Peluso's framing of this concept from that of *capital* in the sustainable livelihoods approach is that it explicitly engages with the relational contexts in which access is negotiated. Attention to these contexts exposes the many layers and even contradictions of power dynamics, from the household level all the way to the global scale, that inform the negation and rules of access.

2.3. Socio-hydrology and hydrosocial theory

I apply ways of studying and conceptualizing water and water access from both socio-hydrology and hydrosocial theory in my analysis. Before delving into their points of divergence, I will briefly discuss one of their shared points of origin. To varying degrees, both have roots in hydrosociology, originally described by hydrologist Malin Falkenmark in 1979. Falkenmark explicitly outlined human and water systems as a linked dichotomy of *water availability* (how much water is physically present) and *water need/demand* (the amount of water required to support any number of societal activities and functionings), both of which change over time.

Within this dichotomy, water is essential to sustain life, but also to support the social, economic, cultural, spiritual, aesthetic, and recreational interests of human societies. Falkenmark's hydro-sociology solidified the foundation for studying coupled human-water systems that socio-hydrology authors would later draw from and expand on, starting with Sivapalan et. al.'s 2012 paper. Although Silvapalan et al. (2012) do not explicitly reference Falkenmark, their discussion of what they refer to as *socio-hydrology* echoes many of the same concepts from Falkenmark's *hydrosociology*, and both branched directly from the field of hydrology.

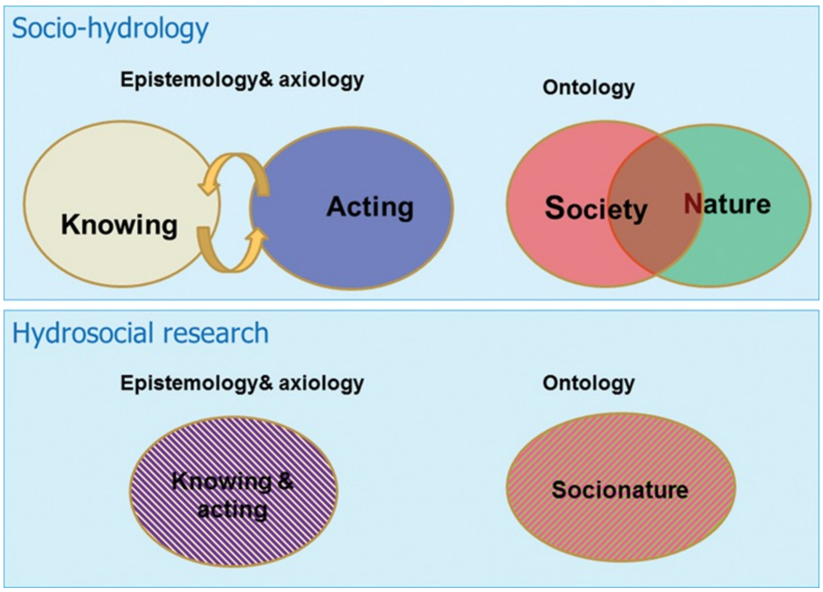

Figure 2.3A. Wesselink, et al.'s (2016) presentation of socio-hydrology and hydrosocial theory's divergence in their approaches and their conceptualisations of society and water.

Like their predecessor, both socio-hydrology and hydrosocial theory maintain that identifying, observing, and describing the feedbacks between human and water interactions are key to understanding potential issues with water access and management. However, they diverge in both their conceptualization and approaches to studying these interactions. Figure 2.3A from Wesselink et al., (2016) offers a visual depiction of their methodological and conceptual differences. My discussion of socio-hydrology and hydrosocial theory's respective foundations, objectives, and methods will detail what this depiction shows as key points of divergence between the two.

2.3.1. Socio-hydrology

Socio-hydrology is a science concerned with the co-evolution of humans and water. Figure 2.3B shows the intersecting feedback loops of societal and hydrological systems in a model developed by Elshafei et al., (2014). Socio-hydrology mirrors social-ecological systems in its methods and its ontological perspective that humans and water are coupled in an overlapping human-water system, as Figure 2.3A depicts (Wesselink, et al., 2016), much like social-ecological systems' merging of the nonhuman biophysical and biological systems and the human in a complex adaptive system (Anderies et al., 2004; Ostrom, 2009). Socio-hydrologic models use long-term observation and historical data on human-water interactions to forecast potential issues, with place-based models providing the most informative and detailed predictions of trajectories. For instance, di Baldassarre et al. (2015) generated a time series socio-hydrologic model using historical empirical data to forecast how the construction of levees may influence future flood vulnerability. Their model predicts that the levees contribute to a higher future vulnerability to floods for the hypothetical society. The levees' efficacy in mitigating flood damage resulted in the collective loss of "flood memory" over time, resulting in the urbanization of flood-prone areas that eventually did experience damage from flooding.

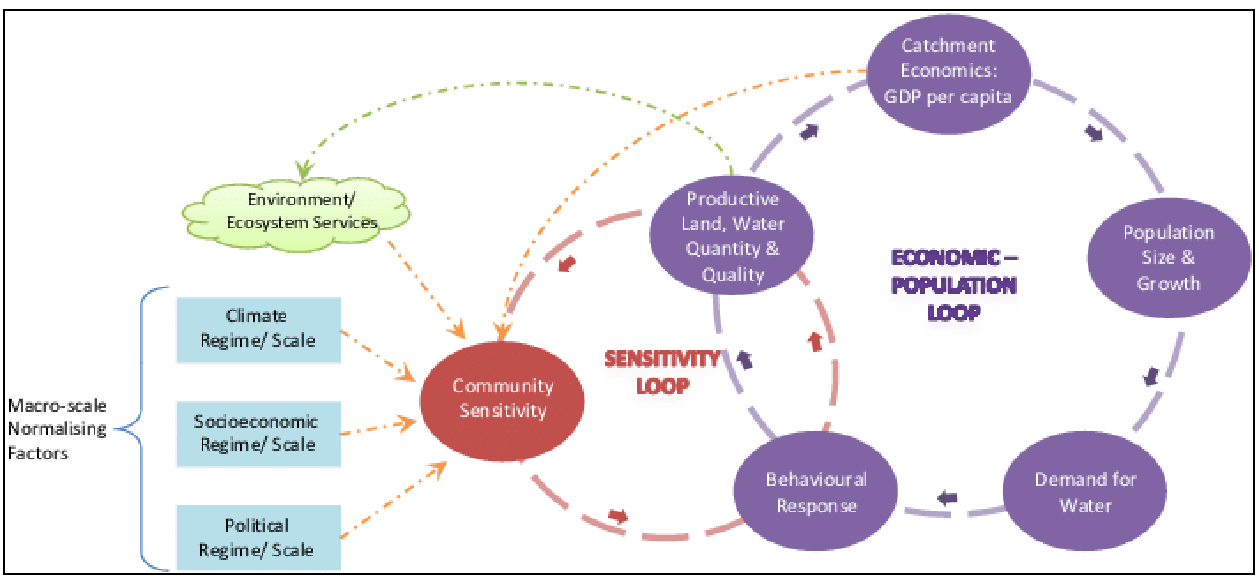

Figure 2.3B. Elshafei et al.'s (2014) conceptualisation of the interconnecting feedback loops of socio-hydrology.

Thus, socio-hydrology aims to capture not only the physical hydrology and infrastructural features of the landscape, but also the behavioural responses from society based on its changing relationship with water. This is also reflected in figure 2.3A, as socio-hydrology assumes that it can predict how a society will respond to a change in the water "side" of the coupled human-water system, suggesting that human-water systems encompass a cycle of knowledge (or lack thereof) leading to predictable behavioural responses that then produce more knowledge (Wesselink et al., 2016).

Socio-hydrology is also explicitly interested in how access to water corresponds to human settlement patterns (Sivapalan et al., 2012). However, socio-hydrologic models alone do not capture all the nuances of humans' relationship with water. Many aspects of the historical, cultural, and socioeconomic contexts that shape the dynamics of access to water resources are not easily quantifiable, if at all. Here, hydrosocial theory's critical approach is better equipped to elucidate the power relations that shape the conditions of access to water.

2.3.2. Hydrosocial theory

Hydrosocial theory's ontology posits that society and water are inextricably linked as socionatures (see Figure 2.3A; Wesselink et al., 2016). It rejects the binary of "society" or "human" and "water", arguing that this binary depoliticizes what are inherently socio-political issues of access to and control of water resources (Boelens et al., 2016; Swyngedouw, 2009). Hydrosocial theory delineates the social power relations surrounding water access and management. Hydrosocial theory's foundations are steeped in political ecology and, more precisely, in Marxian and Foucauldian understandings of unequal power relations, capitalist accumulation, and dispossession of the poor "have nots" (Ross & Change, 2020). As a result, in contrast to socio-hydrology's framing of knowledge containing objective truths that lead to a predictable set of responses, hydrosocial theory states that no single knowledge exists, and, therefore, human responses cannot be forecasted, and no single solution exists to these problems, which are political in nature (see Figure 2.3A; Wesselink et al., 2016).

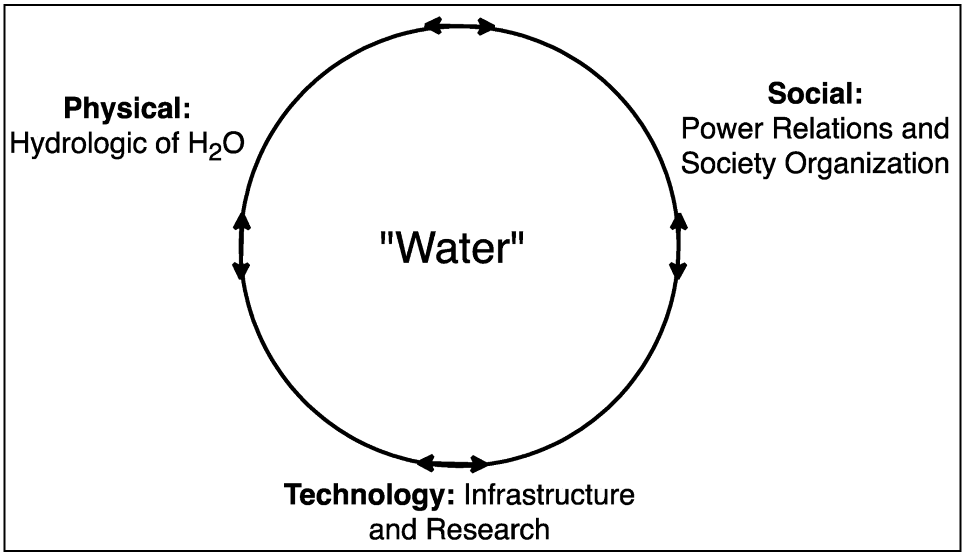

Figure 2.3C. Lint & Budds' (2014) conceptualization of the hydrosocial cycle.

Hydrosocial theory assumes that "water internalizes social relations and politics" in a *hydrosocial cycle* (Lint & Budds, 2014). Figure 2.3C displays Lint & Budds' (2014) conceptualization of the hydrosocial cycle. The hydrosocial cycle plays an active role in the formation of *hydrosocial territories*, the "spatial configurations of people, institutions, water flows, hydraulic technology and the biophysical environment" that dictate who gets access to and control of water (Boelens et al., 2016). The concept is also closely linked with that of *waterscapes* (Flaminio et al., 2022), which also stems directly from political ecology and considers society and nature as inextricably linked (Karpouzoglou & Vij, 2017). Within this complex web of actors, interactions, and processes, hydrosocial theory argues that governance and governmentality are key to mediate the terms of access and to support the production of more egalitarian territories.

Although in many ways hydrosocial theory serves as a solid lens for analysing issues around access to water, it also has some limitations. Hydrosocial research rarely discusses potential solutions to the problems it defines, and the heavy focus on theory can trivialize the physical elements that could be key to developing coherent solutions (Wesselink et al., 2016). These critiques are reminiscent of those of political ecology, as discussed in section 2.2. Finally, hydrosocial research's profound engagement with the theoretical frameworks that hydrosocial theory draws from may be a deterrent to reaching other disciplines. This is because such research can be quite difficult to understand for those without strong backgrounds in the theoretical frameworks (Wesselink et al., 2016).

2.3.3. Linking approaches and principles from socio-hydrology and hydrosocial theory

Individually, socio-hydrology and hydrosocial theory present unique strengths and limitations that elucidate different but interlinking aspects of society and water. However, they also overlap in many regards, and even the points at which they diverge are not inherently irreconcilable. In fact, there may be great benefits to more explicitly linking hydrosocial theory's approach to understanding the social and political issues embedded in the given context with socio-hydrology's modelling and solutions-oriented approach. In recent years, researchers have begun to emphasize the importance of combining the approaches and conceptualizations that socio-hydrology and hydrosocial research embody (Ricart & Kirk, 2022; Ross & Chang, 2020; Rusca & Baldassarre, 2019). Therefore, both of these fields serve as important frameworks in developing my methodology and in the interpretation of my findings.

2.4. The integration of key principles from each theory/approach

The integration of principles from sustainable livelihoods, political ecology, socio-hydrology, and hydrosocial theory establishes a means of comprehensively analyzing surface water distribution and dimensions of access. Figure 2.4 shows how I contextualized the foundational principles from each theory and approach within my analysis. Naturally, each approach has its own particular set of shortcomings, but integrating these approaches together allows each to compensate, to some degree, for the limitations of the others. The sustainable livelihoods framework, for instance, provides an important lens through which I conceptualize the ways in which surface water should be classified to best reflect their usefulness to rural livelihoods. However, this framework is also commonly critiqued for its failure to problematize the role of social and political power dynamics (Turner, 2017). The political ecological perspective of both hydrosocial theory and the theory of access help to address this shortcoming through their deliberate consideration of relational power contexts that shape the mechanisms of access. Additionally, when combined, socio-hydrology and hydrosocial theory better inform access mapping by capturing more of the complexity in the relationship between humans and water. With all the frameworks strategically integrated, their strengths are amplified while their weaknesses are less impactful, forming a comprehensive foundation to guide the process of answering my research questions and discussing the implications of my findings. In the context of my analysis, the integrated framework offers a helpful framing of the issues of surface water availability and access in the Pilcomayo.

The sustainable livelihoods framework offers a means of defining a vulnerability context that considers the climatological and hydrological aspects of the landscape that intrinsically limit the physical availability of surface water in the Pilcomayo. It also provides a logical framing of surface water for the purposes of this study, as it is a vital form of natural capital without which most livelihood strategies would be unsustainable.

The rationale and execution of my methodology aligns with many of the principles and approaches in socio-hydrology. Though I do not use a socio-hydrologic model to explicitly forecast future issues of surface water availability, I rely on the historical hydrological trends to generate a broad, livelihood-centric classification of surface water. My classification of surface water thus serves to link humans and water. Socio-hydrology's objective of demonstrating patterns of human settlement and water access is also reflected in my analysis, as I examine potential correlations between rural settlements' temporal permanence and changes in access to surface water over time. It is important to recall, however, that socio-hydrology's understanding of "access" is limited, in that it does not factor in the relational power dynamics which, in reality, determine who gains access to different types of surface water.

To explore the power dynamics that produce, change, and define the mechanisms of access, I apply concepts from hydrosocial theory and the lens of political ecology when discussing the implications of my results from the access analysis. Though I do not delve into specific social, political, cultural, and institutional interactions when interpreting and discussing the results, I apply concepts from hydrosocial theory and the theory of access to explain, more broadly, what the changes in access may signify in the real-world context for the rural inhabitants affected. Furthermore, I apply my understanding of these theories to articulate the limitations of my analysis, as on its own, it does not explicitly capture the structural and relational mechanisms of access to surface water in the context of the Pilcomayo.

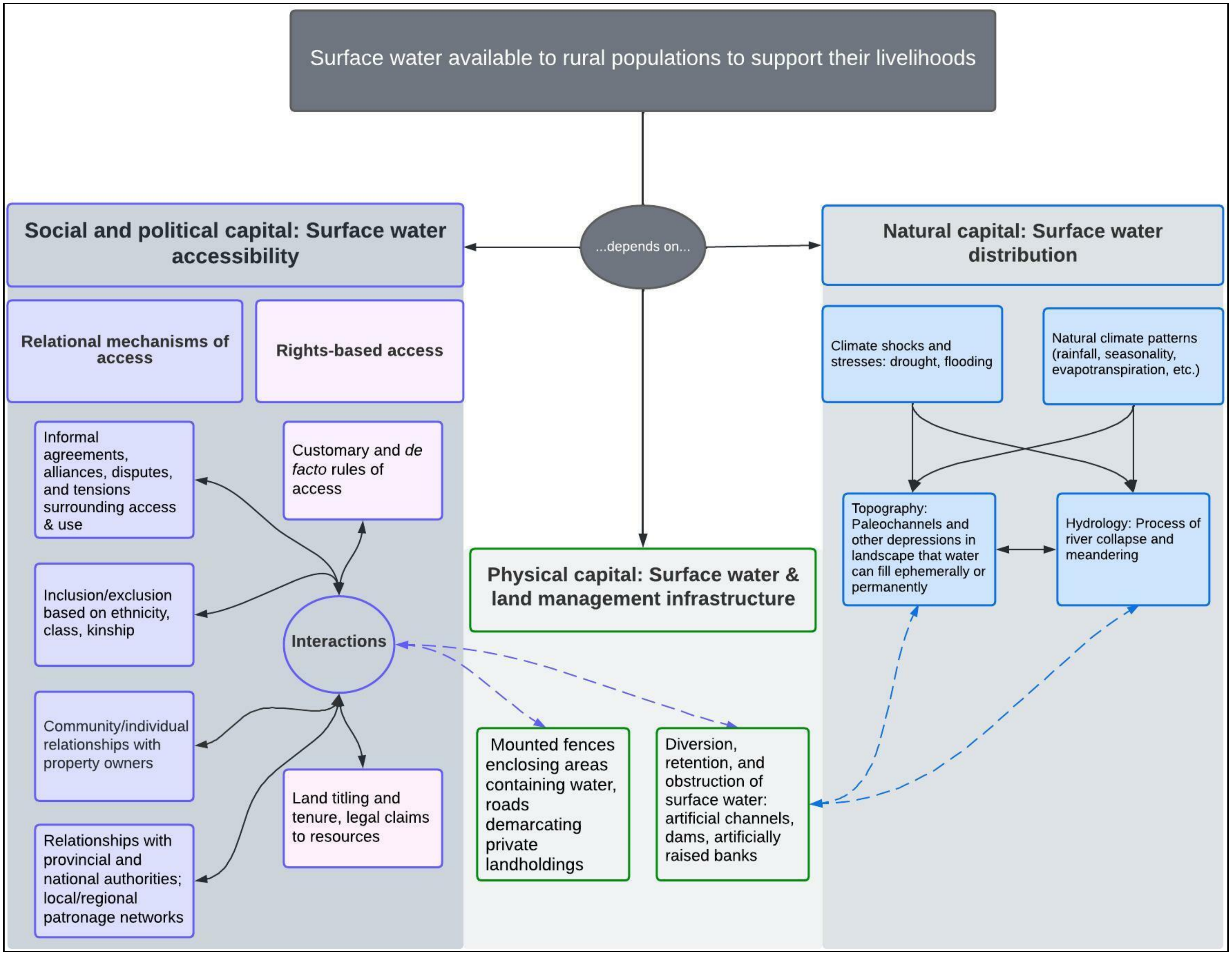

Figure 2.4. The integrated conceptual framework contextualized in responding to questions surrounding surface water distribution and accessibility.

2.5. Chapter conclusion

In this chapter, I reviewed the history, key attributes, and applications of each of the approaches and theoretical frameworks that I apply to my analysis. I highlighted some of the primary critiques of each and explained how the other approaches and frameworks help to compensate for the downfalls of the others. Lastly, I demonstrated how I incorporated the concepts and approaches from each area into a single integrated framework to guide my analysis. With these foundational concepts, I now progress to a review of the context of the Pilcomayo basin to demonstrate how hydro-geomorphological, geopolitical, historical, and social dynamics interact within the region and shape the availability of surface water, agricultural frontier dynamics, and rural populations' access to natural resources.

CHAPTER 3. CONTEXT

In the proceeding sections of this chapter, I describe the geography of the Chaco portion of the Pilcomayo region and the rural populations represented there. In addition, an overview of the history of commodity frontier expansion in the Argentine, Bolivian, and Paraguayan Chaco is offered to contextualize the specific dynamics of social power relations that impact access to natural resources within the basin of the Pilcomayo. The chapter concludes with a discussion of how access has been changing for rural populations in the Pilcomayo basin based on similar processes of dispossession that have occurred in other regions of the Gran Chaco.

3.1. Hydro-geomorphological and geopolitical intersections in the Pilcomayo basin

The Río Pilcomayo originates in the Altiplano of the Bolivian Andes and flows across the plains of the Gran Chaco east towards the Paraguay River (Iriondo et al., 2000). Upon reaching the plains of the Chaco within Argentina and Paraguay, the river meanders frequently and unevenly (Martín-Vide et al., 2012). The Chaco region of the basin covers over 200,000 km^2 (Iriondo et al., 2000), traversing the semiarid Chaco in the west, the humid Chaco in the east, and the subhumid/central Chaco in between the semiarid and humid subregions (see Figure 3.1. The climate is characterized by pronounced wet and dry seasons as well as generally warm temperatures year-round ranging from 12°C-30°C (Rubí Banchi & Cravero, 2010).

As a transboundary river, the Pilcomayo and, consequently, the people and ecosystems reliant on the river, are inextricably linked to everything that happens within and around the tributaries, confluences, and landscapes that form the larger basin. Thus, despite the Pilcomayo's origins in the Bolivian altiplano well beyond the biome of the Gran Chaco, upstream biogeochemical inputs and hydrological changes have considerable impact along the length of the entire river. For instance, in July of 2022, a dike holding in a contention pond filled with mine tailings was reported as broken in the Bolivian department of Potosí, a major mining municipal department in Bolivia that falls outside of the region of the Chaco plains but within the basin of the Pilcomayo (Gonzáles & ABC Color, 2022). Although, the contamination did not reach the river, in part due to the region being in its dry season at the time of the leak (Gonzáles & ABC Color, 2022), this is not the first time that the Pilcomayo has faced the risk of, or, in many cases, direct receival of toxic mine tailings, as the department of Potosí has a centuries-long history of mining (Correo del Sur, 2022). Petroleum and natural gas extraction also take place in the basin, with most active sites of exploitation occurring in Bolivia. In fact, natural gas and petroleum extraction and pipeline development occurs throughout the Indigenous Weenhayek territory along the eastern border of the Pilcomayo south of Villa Montes, Bolivia, well within the region of the Gran Chaco (Humphreys Bebbington & Cortez, 2021). These extractive industries have impacts that spread far beyond the municipal and international borders in which they occur.

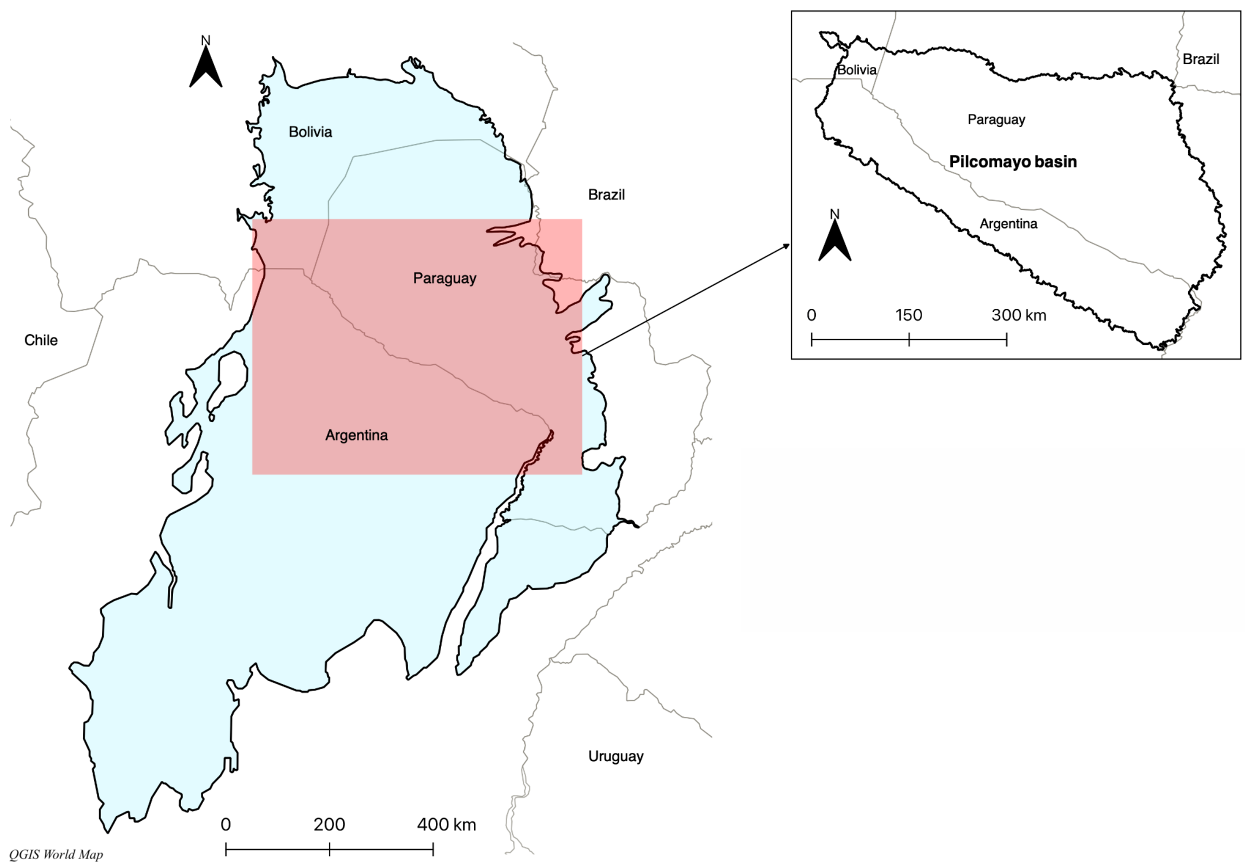

Figure 3.1. The biome of the Gran Chaco outlined in blue and the specific subregion of focus within the Pilcomayo region displayed in the overview in the top right.

Geopolitical tensions and disputes in the transnational bounds of the basin can quite literally shape the river itself and generate hydrological, social, and political conditions and processes that impact the people who live in the region. Several key historical events offer insight into the geopolitical contexts that have developed over time and whose legacies continue shaping the human and physical geography of the Pilcomayo River and its basin. Between 1864-1870, Paraguay fought against Argentina, Brazil, and Uruguay in the War of the Triple Alliance (Gordillo & Leguizamón, 2005). The devastation of the war forced Paraguay to cede territory to Argentina and Brazil and to sell much of its public land to private foreign investors (Caldas et al., 2011), an historical factor that has influenced the development of the agricultural frontier in Paraguay in ways that will be discussed in Section 3.4.3. In 1876, Paraguay and Argentina signed The Irigoyen–Machain Peace Treaty, and in 1878, then U.S. President Rutherford B. Hayes was selected to arbitrate remaining territorial ambiguity (Testa, 2015). Hayes arbitrated in favor of Paraguay, requiring Argentina to cede territory between the Río Verde and the Río Pilcomayo to Paraguay (Gordillo & Leguizamón, 2005). Thus, the Pilcomayo was defined as a physical transnational boundary between Argentina and Paraguay.

However, the river is not a stable border between the two countries (Giraut & Lupano, 2015). Its uneven meanders and receding channel due to siltation associated with its large sediment load cause it to change course with relative frequency (Martín-Vide et al., 2012). Therefore, for several decades, there has been marked uncertainty regarding the consistent arrival of water to support the rural populations who rely on the river and its associated wetlands in each country (Gordillo & Leguizamón, 2005). To resolve this problem of uneven water distribution between the two nations, they agreed to execute a river channelization project starting in 1991 known as "The Pantleg Project", El Proyecto Pantalón, in Spanish, so called because of the bifurcation of the main channel of the Pilcomayo into two "legs", one for each country (Brown et al., 2018). Nevertheless, political conflicts arose even from this compromise, as the Paraguayan canal was constructed inadequately, causing much of the water from the Pilcomayo to travel towards Argentina's canal (Gordillo, 2001). A severe drought in the Paraguayan Chaco from 1992-1994 exacerbated this situation and resulted in Paraguay constructing a new canal and Argentina partially filling its own to facilitate a more equal distribution (Gordillo & Leguizamón, 2005). Yet this still did not resolve the problem of water distribution. Both Argentina and Paraguay have continued to construct canals along the river to feed wetlands and supply water to rural communities, but the canals require constant maintenance to ensure that they are not silted in from the Pilcomayo's large sediment load (Martín-Vide et al., 2012). In general, artificial channels and other anthropogenic modifications to the landscape such as dams have had many impacts, some of which cannot be characterised as unequivocally positive or negative, on the ecology, hydrology, and political climate of the Pilcomayo. Thus, the issue of surface water availability in the areas surrounding the river is entangled in geopolitical and hydro-geomorphological contexts that feed into one another and have discernable impacts on rural populations and the sustainability of their livelihoods.

3.2 Surface water availability and use

Rural populations living within the riparian zone of the Pilcomayo depend directly on the river Pilcomayo and its associated wetlands, *cañadas* (lakes that form in ravines), and *charcas* (usually ephemeral ponds that form in depressions in the landscape) fed by seasonal flooding of the river to sustain their various livelihoods (Brown et al., 2018; Baumann & Cavallero, 2008). The river also directly supports a variety of fish species, the migratory *sábalo* (*Prochilodus lineatus*) being perhaps the most important for subsistence and commercial purposes (Baigún et al., 2012). The river's associated wetlands are an important source of water for wildlife that is dependent on the river's seasonal flooding, and even artificial channels that have been constructed along the river can serve as important sources of water for the local fauna (Baumann & Cavallero, 2008). The ecosystems around the river are regulated by its periodic flooding in conjunction with topographic variation throughout the landscape, the latter of which is also directly influenced by the river's geomorphological and hydrological tendencies.

The Pilcomayo carries enormous quantities of sediment that contribute to the channel filling itself in, and as the river moves downstream, the channel eventually begins to sit at the same level or slightly higher in elevation than the surrounding floodplain due to the sediment deposits (Iriondo et al., 2000). This process results in the river obstructing itself from the channel pathway, resulting in flooding each wet season, which contributes to the formation of wetlands (Martín-Vide et al., 2012). Simultaneously, the process also results in the abandonment of wetlands in areas further downstream, as the constant filling of the river channel with sediment results in the point of self-obstruction shifting further upstream with each wet season (Martín-Vide et al., 2012). The most recent large-scale example of the latter case occurred in the area of the *Estero Patiño*, a former wetland in the Paraguayan municipality of Presidente Hayes. The wetland consistently received the Pilcomayo's waters until around the year 1944, when the river shifted its course southeast towards Argentina, forming the wetland that is today known as *Bañado La Estrella* in the Argentine province of Formosa and leaving the *Estero Patiño* completely dry by the early 1980s (Baumann & Cavallaro, 2008; Lamenza et al., 2019).

Despite the grand size of the basin, much of its area does not contribute to the river's hydrological discharge, as the Pilcomayo has changed its course multiple times throughout its history, retreating upstream and abandoning its former channels as well as the wetlands those channels fed due to the self-obstruction generated by its large sediment load (Iriondo et al., 2000). As such, a large portion of the rural population inhabiting the basin is not actually located within the riparian zone (i.e., floodplain) of the river. The rural populations living in areas beyond the reach of the floodplain rely on ephemeral and permanent surface water sources including intermittent streams, wetlands, *cañadas*, *charcas*, and rainwater tanks (Gordillo & Leguizamón, 2005). These sources of water also support the native terrestrial vegetation, wildlife, and household gardens that rural communities rely on as sources of food, medicine, and materials for construction and artisanal production, as well as small-scale livestock production and even certain forms of agriculture (Brown et al., 2018).

In areas beyond the reach of the river's flooding, surface water is usually recharged by rainwater (Serrati, 2016). As in the riparian zone, the rain-fed *charcas*, *cañadas*, and *bañados*, even if ephemeral, provide a crucial source of water for direct consumption by livestock, wildlife, and sometimes people. As such, the seasonal cycles of rain and flooding that recharge these surface water resources support a host of livelihoods such as hunting/gathering, livestock production, wild honey production, and charcoal and fuel wood production. The native vegetation supported by these water resources even serve auxiliary functions that benefit wildlife and livestock, such as providing shade to animals during the hot day (FAO, 2019). Even channels long abandoned by the river in its previous course, frequently referred to as paleochannels (*paleocauces*), of the Pilcomayo serve an important role in supporting different ecosystems. Paleochannels located in elevated portions of the landscape support both *quebracho* forest (hardwood species of the genus *Schinopsis*) as well as grasslands, often dominated by *aibe* (*Elionurus muticus*), a perennial plant that grows well in the sandy soils typical of paleochannels (Baumann & Cavallero, 2008; Brown et al., 2018). Additionally, hydrophilic herbaceous vegetation tends to dominate topographic depressions within the landscape that are prone to flooding, while shrubs and palms grow along the slightly more elevated areas of land, supporting a savannah ecosystem (Baumann & Cavallaro, 2008).

Although drinking wells are an essential source of potable water for many smallholders and communities in the region (Levers et al., 2021), these are not discussed in detail in this study since these are sourced from groundwater. Groundwater is not considered in this study because the hydrological and geomorphological processes that generate and feed groundwater and the issues surrounding safe access to groundwater are distinct from those involving surface water, and data on its availability is scarce or unavailable for much of the region.

3.3. People and livelihoods of the Pilcomayo basin

The Pilcomayo basin is home to several linguistically, ethnically, and culturally distinct populations, including Indigenous groups such as the Pilagá, Toba-Qom, Tapiete, Weenhayek and Wichí, Nivaclé, Guaraní, and Chorote/Manjuí, as well as *mestizo* rural smallholders and Mennonite settlers (Braunstein, 2005; Brown et al., 2018; le Polain de Waroux et al., 2021). Between and within these groups, there is a broad range of livelihoods and perspectives on how land and water resources should be used. Throughout this proposal, the umbrella term *rural populations* is used to refer specifically to the aforementioned Indigenous and mestizo smallholder populations of the Pilcomayo basin. These groups are referred to collectively based on the premise that they share two qualities that are central to this study: 1) they depend on similar types of land and water resources for their livelihoods, to varying extents, and 2) they face the same threat of reduced access to these resources as a consequence of the advance of the agricultural commodity frontier (Serrati, 2016; Brown et al., 2018).

Although the Mennonite colonies also harbor a diverse rural population that faces water challenges, their occupation in the Pilcomayo basin has also greatly influenced the expansion of the agricultural frontier in the region, whether directly through participation in commodity booms or indirectly through their role as agricultural pioneers whose success changed perceptions of the economically productive viability of the landscape (le Polain de Waroux et al., 2021). For this reason, I will discuss the Mennonite population in this chapter to elucidate their unique dynamics, as these have had direct and indirect impacts on the landscape and the other rural populations occupying it, but the Mennonites are not considered in the access analysis. This is because the structure of Mennonite colonies and their mechanisms of access are distinct from those of Indigenous peoples and *mestizo* smallholders. Therefore, although water scarcity overall is a concern for the Mennonite colonies of the Pilcomayo basin, issues in accessing surface water are driven primarily by climatic and hydrological factors that limit the distribution of surface water. In contrast, for Indigenous peoples and *mestizo* smallholders, access to surface water is limited not only by the physical availability and distribution of surface water, but also by the enclosure of the commons, a process directly driven by the expansion of the agricultural commodity frontier.

3.3.1. Indigenous peoples

Indigenous communities of the Pilcomayo practice a variety of livelihood strategies depending on their geographic location. For those living in close proximity to the river, such as the Weenhayek and Tapiete communities in Bolivia and some Toba, Wichí, Manjui, Nivaclé, and Guaraní communities, fishing is a very commonly practiced subsistence activity (Humphreys Bebbington & Córtez, 2021; Gordillo & Leguizamón, 2005). In fact, some communities, such as many of the Weenhayek, have developed a regional economy based on fishing, as the arrival of refrigeration in 1960 made the transport of fish to other markets in Bolivia feasible (Humphreys Bebbington & Córtez, 2021). For others, fishing remains primarily a subsistence and very small-scale commercial activity (Brown et al., 2018). Hunting and gathering, wild honey harvesting, and small-scale agriculture and livestock production are also widely practiced by many Indigenous peoples as primary or supporting livelihoods (Camino et al., 2018; Seghezzo et al., 2017; Kamienkowski & Arenas, 2012a). Some groups produce artisanal figurines, traditional skirts, and bags that are sold to visitors and at local and even regional markets, such as among Manjuí and Nivaclé communities in the Indigenous community of San Agustín in Paraguay.

Many individuals of different Indigenous groups also work in agriculture and construction. In the Central Chaco of Paraguay, after the arrival of Mennonite settlers in 1926 (le Polain de Waroux et al., 2021) and the start of the Chaco War in 1932, several Indigenous groups within the Enlhet-Enenlhet language family, including the Angaité, Enxet, and Sanpaná lost their territories and were pushed to settle permanently near Mennonite colonies to work in the agriculture, construction, and transport sectors (Hirsch et al., 2021). Today, many communities from these groups remain in close spatial proximity to the Mennonite colonies in Paraguay. People of the Manjuí, Nivaclé, and Guaraní communities closer to the river also migrate to work in the Mennonite colonies to work in these sectors, though they often also practice fishing as a livelihood practice.

The Guaraní-Chiriguano of Bolivia also migrate to work on agricultural land of Mennonite colonies in the municipality of Charagua, and, in the mid 20th century, people from this community would also work during the harvest season for sugar cane in Santa Cruz (Bazoberry Chali, 2003). Similarly, in Argentina, towards the end of the 19th century into the early 20th century, many people of the Toba-Qom and Wichí ethnic groups began to migrate seasonally to sugar refineries located in the northwest region of the country (Camino et al., 2018; Gordillo & Leguizamón, 2005). Nevertheless, by the late 1960s mechanization had rendered much of the physical human labor obsolete (Gordillo & Leguizamón, 2005). As such, work in the agricultural sector tends to be intermittent for most individuals of Indigenous communities.

The governments of the three countries through which the river passes also provide some cash assistance and development initiatives for Indigenous peoples and poor rural communities in general. For example, the Paraguayan government also offers cash transfers to Indigenous communities and smallholder families through social welfare programs such as the *Tekoporã* program and the *Pensión Alimentaria Para Adultos Mayores en Situación de Pobreza* (Ministerio de Desarrollo Social, n.d.). In Argentina, communities of Indigenous groups such as the Wichí and Toba sometimes also receive social government aid, though the extent to which this meaningfully supports these populations and their optimal livelihood outcomes is not definitive (Gordillo, 1993).

3.3.2. Mestizo smallholders

In this study, unless otherwise specified, the term *mestizo* smallholder refers collectively to a broad racial/ethnic and socioeconomic demographic of the rural population of the Pilcomayo basin. The word *mestizo* refers to the mixed Indigenous and European racial identity of these individuals. It encompasses those who principally identify themselves ethnically as either *criollo* (those of mixed descent but with recent rural Argentine roots) or *latino* (often referring to those from Paraguay who are of mixed Guaraní and European descent) as well. "Smallholder", then, refers to the class identity of these individuals as users of a relatively small amount of land, in contrast to the larger-scale ranchers and crop farmers that are driving the agricultural frontier. Those who identify themselves socioeconomically, or even politically, as *campesino* or *poblador* are encompassed in the word "smallholder". There are also many Indigenous smallholders throughout the Gran Chaco, but the majority of the Indigenous populations in Argentina, Bolivia, and Paraguay live in larger, concentrated communities, in contrast to the more isolated and spatially scattered settlements of most *mestizo* smallholders (Gordillo, 2014, p. 66).

Along the Pilcomayo and throughout the Argentine Chaco, non-Indigenous smallholders usually self-identify as *criollos* (Gordillo, 2014, p. 53). The *criollos* of the northwest Chaco, including along the Pilcomayo, are descendants of mixed-race settlers who arrived to the Chaco from the Andean region in the 16th and 17th centuries and began widely spreading across Chaco at the start of the 1900s (Dasso, 2010). Along the banks of the Pilcomayo, many of these *criollo* smallholders from Argentina also crossed into Paraguay, especially since state presence prior to the Chaco War was minimal in this region up until the early 20th century (Hirsch et al., 2021). However, the Chaco War of 1932 would send many *criollos* back across the border to Argentina, and it wasn't until after the war's end that *mestizo* smallholders, including the *criollos*, would begin populating the Paraguayan Chaco in small family groups (Kalisch, 2021).

The livelihoods of *mestizo* smallholders in the Gran Chaco center principally on livestock rearing, particularly in the form of extensive cattle ranching (Altrichter, 2006; Seghezzo et al., 2011; Brown et al., 2018). Many practice hunting and gathering as well, though generally to a much lesser degree than Indigenous peoples, as these tend to be more opportunistic livelihood practices for *mestizo* smallholders (Camino et al., 2018). Apiculture and wild honey harvesting are also widely practiced by smallholders for personal consumption as well as small scale production to sell locally and regionally (Kamienkowski & Arenas, 2012b). In addition, some create artisanal goods from forest and animal products and engage in extraction of timber for charcoal, fence post, and fuel-wood production (Bucher & Huszar, 1999; Guzmán et al., 2012). Because many *mestizo* smallholders live in precarious states of land tenure, they often also turn to wage labour on larger farms (Gordillo, 2014, p. 65), with some migrating seasonally to harvest olives, sugar cane, blueberries, and other agricultural products (Quaranta & Blanco, 2012). For those smallholders without titles to their land, they may support their cattle production by paying rent to the landowners to pasture their cattle on private landholdings (Gordillo, 2014, p. 65). Many also receive social aid through the government, often through the same programs that also serve Indigenous communities (Camino et al., 2018).

3.4. Agricultural frontier expansion in the Gran Chaco

Given that the Chaco region of the Pilcomayo basin extends into Argentina, Bolivia, and Paraguay, it is necessary to contextualize the development of each country's respective agricultural frontier. The three countries' trajectories are directly interconnected spatially through the Pilcomayo basin, and many aspects of their historical, political, and economic mechanisms of agricultural frontier development share important similarities. Even where these trajectories diverge, the social, political, and (in the case of the Pilcomayo especially) hydrogeomorphological impacts of decisions made by different iterations of the state and by "waves" of individual actors with access to capital and political power establish legacies from which the current agricultural frontier is built (Kronenburg García et al., 2022).

3.4.1. Agricultural frontier Expansion in the Argentine Chaco

Morello et al., (2005 & 2013) identify several periods of occupation of the Gran Chaco and characterize each period according to the actors involved and the specific resources of value. Well before the colonial period, Indigenous peoples frequently used fire to manage woody vegetation growth, promoting the mosaic of different herbaceous and woody ecosystems across the region and particularly favoring grasslands. In addition, smallholders entered the region in search of honey and wax but also introduced large livestock along rivers of the Gran Chaco. Throughout the 18th and 19th centuries, military expansion into strategic areas of the Gran Chaco, including exploration of the Río Pilcomayo (Gordillo & Leguizamón, 2005), also facilitated frontier development. The military began establishing its foothold by building forts along a northwest to southeast line from the Río Bermejo to the Río Salado and ending in the province of Santa Fé. A colonial system of large properties controlled by landowners of European descent developed, and in 1850, a large amount of public land in the province of Santiago del Estero was sold, further consolidating land in the hands of a few powerful landowners (Paz & Jara, 2020).

In the late 19th century, *criollo* smallholders practicing extensive cattle ranching began exploring territories further from the main rivers of the Gran Chaco such as the Bermejo and the Salado-Dulce (Morello et al., 2005 & 2013). Meanwhile, large-scale cattle breeders and ranchers grew their operations and began to cultivate monotypic pastures of alfalfa to fatten livestock more efficiently. The widespread introduction of large livestock led to changes in ground cover, such as the regional endangerment of native herbaceous vegetation such as the *simbol* (*Pennisetum frutescens*), and reduced leaf litter, leading to suppression of the fire regime and, consequently the encroachment of woody species in grasslands (Grau et al., 2014). Around the same time, selective timber extraction for railroad ties, charcoal, and fence posts also expanded, and around the 1920s, the tannin industry began developing (Morello et al., 2005 & 2013).

The selective logging and species preferences of the tannin industry led to changes in the natural forest structure. Morello et al. (2005 & 2013) note that in both the timber extraction and tannin industries, the main species targeted for extraction and exploitation in both industries were from the genus *Schinopsis* (commonly called *quebracho*). During this period, extraction of essential oils from *Bulnesia sarmientoi* (commonly called *palosanto*) also led to increased pressure on this species. Meanwhile, cattle ranching contributed to overgrazing and other associated changes in the natural vegetation cover as it continued to expand during this period. Native fauna faced increased pressure due to the changes to the ecosystem, and some species were also specifically targeted for the economic value of their pelts, as was the case for several fox and feline species. Nevertheless, by the 1950s and ‘60s, both industries began to slow, with timber extraction for railway ties reducing as a result of reduced demand for railway ties and the discovery of a new substitute plant species for tannin production in Kenya and modern-day Zimbabwe (Morello et al., 2013; Vázquez, 2013, p. 92).

Morello et al. (2005 & 2013) identify the cotton commodity frontier as the next wave of expansion, occurring simultaneously with the aforementioned industries. Cotton production began at the end of the 19th century, and by the 1930s, a network of colonies built around the industry had developed with the support of the Argentine government at the time. However, with the introduction of genetically engineered soybeans in the 1970s and several failed cotton harvests in the 1990s, the reign of cotton would eventually tumble in the wake of soy's rise as the newest preferred commodity. A subsequent soy boom attributed to the increase in soy prices, the adoption of genetically engineered soy seeds resistant to glyphosate, and the introduction of new technologies took place in the 1990s and 2000s (le Polain de Waroux et al., 2018).

At this point, agricultural commodity production began to advance even more rapidly in Argentina, aided by technological and strategic adaptations implemented. For instance, no-till cropping improved soil water retention, and the introduction of storage bags allowed agricultural development to occur in areas lacking storage infrastructure (le Polain de Waroux et al., 2018). Soy cultivation has been identified as both a direct and indirect driver of deforestation in the region (Gasparri et al., 2013; Fehlenberg et al., 2017). Argentina's economic crisis in 2001, which led to the devaluation of the national currency, and the increased global value of soy stimulated increased soy production, and, accordingly, deforestation in Argentina overall (Gasparri & Grau, 2009).

Deforestation may have also been carried out preemptively in anticipation of the country's Forest Law, which was passed in 2007 and mandated that provinces classify land into one of three categories of conservation value (Gasparri & Grau, 2009; Ley de Bosque Nativo, art. VI). Overall, the implementation of this law appears to have reduced deforestation in the country, though at varying spatial and temporal scales (Nolte et al., 2017). The spatial-temporal variation in deforestation reduction could be a result of the law's provincial-level focus, which appears to have led to inconsistencies in the actual implementation of the law and has limited the potential for larger scale connectivity of native ecosystems (Aguiar et al., 2018). This may be due to large-scale producers with sufficient political sway encouraging some provincial politicians to increase the area of land under the categories of lesser conservation value (Seghezzo et al., 2011).

Even with the implementation of the Forest Law and available land becoming scarce in the late 2000s, investors from the agribusiness sector sought to expand the agricultural frontier further into other parts of the Chaco. The most recent agricultural frontier of the Argentine Chaco is, in fact, the region of the Pilcomayo. Previously perceived as an undesirable area for agricultural exploits, it become more appealing after the completion of a major road (road 81), facilitating access to the region, leading to an expansion from the lower Pilcomayo in the eastern portion of the province of Formosa to the northwest (le Polain de Waroux et al., 2018). In addition, experiments with improved pasture and relaxed implementation of the Forest Law may have also contributed to the Pilcomayo positioning as the next agricultural frontier (le Polain de Waroux et al., 2018). A geographically separate frontier in northwest Argentina is now approaching the Pilcomayo as well: since the 1980s, the agricultural frontier in Tartagal, stemming from the Yungas ecoregion of the Andean foothills, has been moving east towards the region of the Pilcomayo (le Polain de Waroux et al., 2018).

3.4.3. Agricultural frontier expansion in the Paraguayan Chaco

The Pilcomayo basin comprises a much larger area of the Paraguayan Chaco than the Argentine Chaco, and several historical, political, and demographic circumstances aligned to make development in the Paraguayan Chaco occur quite early and rapidly, accelerating the processes of dispossession and limiting the capacity of Indigenous and smallholders to mobilize to disrupt these processes. One of the first major events that had direct consequences in frontier and access dynamics in the Paraguayan Chaco was the War of the Triple Alliance, in which the country fought and lost against Argentina, Brazil, and Uruguay. In 1870, Paraguay's government was forced not only to cede an estimated 156,415 km^2 of its territory to Argentina and Brazil (Vázquez, 2013, p.44), but also to sell a large portion of its public land to foreign private investors in order to cover its war debts, a process that dispossessed many Indigenous peoples of their land (Caldas et al., 2015). The enormous quantity of public land that Paraguay sold to cover its debt from the War of the Triple Alliance set the foundation for foreign investment and control in the country. Ultimately, a total of 13 million hectares of land were in the hands of only 79 private investors, including several Argentine, Anglo-Argentine, Brazilian, and European companies (Vázquez, 2013, p. 52). The economic influence of these companies, several of which had partial or full roots in Argentina, set Paraguay on a similar frontier trajectory as Argentina in the late 19th to early 20th centuries, as extraction of timber and exploitation of tannins, particularly from *quebracho* species, was implemented (Vázquez, 2013, p. 54 & 56). The active presence of foreign economic interest would later have important implications during the Chaco

War between Bolivia and Paraguay.In fact, Argentina quite publicly supported Paraguay throughout the war because of its vested interest in protecting the tannin industry in Paraguay in which Argentina was so heavily invested (Vázquez, 2013, p.89).

In the 1926, Mennonite colonists from Canada arrived in the Paraguayan Central Chaco, a semiarid subregion of the Gran Chaco, and formed the colony of Menno, and only 4 years later, Mennonites escaping persecution from the Soviet Union would form the nearby colony of Fernheim (le Polain de Waroux et al., 2021). Although some local politicians and the general population were concerned that the Mennonite occupation could lead to a Mennonite state within the Paraguayan state, the Paraguayan government was largely in favor of the occupation (Breithoff, 2020, p.40). This is because the federal government believed that the Mennonites' presence provided multiple strategic advantages in the region. First, their high work ethic made them the ideal forces to "civilize" the Chaco through establishing an agriculture-based society in the center of the region; second, and rather ironically considering the pacifist ideals of the Mennonite faith, the services that Mennonite communities were able to provide became integral to the Paraguayan military schema during the Chaco War against Bolivia between 1932-1935 (Breithoff, 2020, p.41).

The reasons for the escalation of the war are embedded in both external geopolitical circumstances and, within each involved country, the internal national trauma surrounding the losses of territory that both countries had suffered. Just as Paraguay lost a significant portion of territory in the aftermath of the War of the Triple Alliance, Bolivia lost its access to the sea in the War of the Pacific against Chile. Complicating matters further, Bolivia, unlike Paraguay, does not have a river network that facilitates access to regional and international markets; as such, the two landlocked countries were negotiating to arrive at an agreement defining their borders with one another, but when diplomacy failed, an armed conflict ensued (Vázquez, 2013, p. 79). The notion of losing even more of its land after the War of the Triple Alliance, the devastation of which was still well in living memory, was unfathomable (Breithoff, 2020). In addition, the Chaco region was viewed as a potential petroleum reserve, and the governments presumably sought to exploit this resource (Vázquez, 2013, p.81).

Given their profound understanding of the terrain and ecology of the Chaco, the Indigenous groups of the region were invaluable guides and sources of knowledge for both nations (Breithoff, 2020). The complex social relationships between the different groups also influenced the nature of alliances with one nation-state or the other, and, arguably, even the nation-states used the complexity of Indigenous identity to fuel battle fervor. More specifically, both Bolivia and Paraguay claimed their Indigenous status to legitimize their ownership of the Chaco. The Paraguayan side cited their Guaraní heritage and arguing that the Guaraní peoples' occupation of the Chaco justified their claims to the territory, while the Bolivian side framed the country's Indigenous Quechua and Aymara roots as valid grounds for Bolivian claims to the territory (Breithoff, 2020, p. 33).

In spite of the nations' opportunistic rhetorical framing of their national identities in terms of indigeneity and the fact that the aid of the Indigenous peoples of the Chaco was key in either side's ability to ultimately win the war, neither nation recognised the Indigenous peoples of the Chaco as sovereign societies whose relationship with the landscape aligned with their notion of "civilisation". On the contrary, both the governments of Bolivia and Paraguay explicitly viewed the territory as void of their conception of "civilisation" (Breithoff, 2020, p.31-32). As such, although removal of Indigenous groups was not an objective of this war, ultimately, this absence of consideration for the Indigenous occupation of the territory links to a broader pattern of exclusion and exploitation of Indigenous communities of the Chaco.

The Chaco War ended in 1935 when the Paraguayan army forced the Bolivian troops to retreat, resulting in the signing of an armistice and Paraguay keeping a large portion of the contested region (Vázquez, 2013, p. 86). Nevertheless, when speaking with locals of the Paraguayan Chaco, including the inhabitants of the region of the Pilcomayo, the war's legacy remains palpable. The massive displacements and resettlements that occurred as a direct result of the Chaco War led to people being alienated from their territory and livelihoods and even separated from their families due to the limited mobility that the violent war frontier imposed (Breithoff, 2020, p.31). This is particularly true for Indigenous peoples in Paraguay, Argentina, and Bolivia, who found themselves forced to settle in sedentary communities (Hirsch, 2021).

In Paraguay especially, there was a wave of resettlement of Indigenous peoples that brought them in increasingly close proximity to Mennonite communities. In the mid-20th century, Paraguay saw the arrival of a second wave of Mennonite colonists coinciding with a period of foreign companies withdrawing from the Paraguayan Chaco due to the tannin industry cycle of both Paraguay and Argentina drawing to a close (Vázquez, 2013, p. 92). Around this time, a new commodity crop came into wide production: cotton. The cultivation of cotton and the exploration of new cultivars adapted to the Chaco's climate was widely supported by the state, and for many Mennonite farmers, this became a way of integrating themselves into the national economy (Vázquez, 2013, p. 97). As in Argentina, cotton prices dropped significantly in the 1990s, but two other commodities had already arrived to occupy cotton's place in the Paraguayan Chaco: beef and dairy. Once again, the Mennonite colonies were the main driving force behind these two industries, and because land was readily available at a relatively low price in the Paraguayan Chaco, the Mennonite population was able to expand rapidly across the landscape through local land acquisition (le Polain de Waroux et al., 2021). Their swift acclimation to the frontier would make them invaluable to the future waves of foreign investors who would arrive shortly in the region to pursue their own agricultural ventures.

In the 1980s, a few French and German companies also began investing in the semiarid Paraguayan Chaco (le Polain de Waroux et al., 2018). Then, in the 1990s, the Paraguayan Chaco experienced an influx of Brazilian ranchers and investors who began working closely with the Mennonite colonists, who possessed the knowledge, infrastructure, and services that these newer arrivals required to expand in the region (le Polain de Waroux et al., 2021). This expansion was facilitated by the introduction of new, more efficient deforestation techniques and local research on drought-resistant pastures (le Polain de Waroux et al., 2018). Around the mid-2000s, Brazilian investors began to push further into the western semi-arid Chaco (le Polain de Waroux, 2019). Around the same time, between the 1990s into the 2000s, the global soy boom that was driving agricultural expansion in Argentina encouraged Argentine producers to explore agricultural production ventures in Paraguay (le Polain de Waroux et al., 2018). In the late 2000s, several Uruguayan investors also began to invest heavily in the region, enlisting local property managers, usually from the Mennonite community, to manage the daily operations of their properties (le Polain de Waroux, 2019).

Throughout the historical time frame reviewed, peasant and Indigenous mobilization against the expansion of the agricultural frontier was quite limited relative to other Latin American countries. Perhaps the single most impactful factor of the 20th century that delayed such mobilization is the military dictatorship that ruled Paraguay from 1954 until 1989, making it the last to fall in South America and ensuring that any dissent or attempts to mobilize were effectively quelled during its reign (Hirsch, 2021). This stands in contrast to neighboring Argentina and Bolivia, where Indigenous and peasant movements as well as agrarian reform have played important roles in shaping the development of the agricultural commodity frontier.

3.4.3. Agricultural frontier expansion in the Bolivian Chaco

Bolivia's history of agricultural frontier expansion in the eastern lowlands that encompass the Chaco is tied closely to a series of agrarian reforms, hydrocarbon ventures and exploitation, and the political reframing of the link between extractivism and "progress". The eastern lowlands of Bolivia were populated almost exclusively by Indigenous peoples, especially the Weenhayek, Tapiete, and Guaraní up until the 19th century (Hirsch et al., 2021), at which point cattle ranching became perhaps the first large-scale non-Indigenous economic agricultural activity to take place in the region (Bazoberry Chali, 2003). In the early 20th century, the Bolivian state began expanding its presence in the lowlands by building forts and roads along the Pilcomayo, and around the same time, natural gas and petroleum exploitation also developed (Hirsch et al., 2021). Hydrocarbon speculation also encouraged Argentina's investment in a railway between Santa Cruz in Bolivia's eastern lowlands and Yacuiba, a city located right in the crest-shaped border region between the two countries (Bazoberry Chali, 2005). There are also theories that the Chaco War of 1932 through 1935 between Bolivia and Paraguay was caused in part by the two country's speculative interest in exploiting petroleum reserves in the region of the Chaco under dispute (Bazoberry Chali, 2005; Breithoff, 2020, p. 48; Vázquex, 2013, p.81).

Although the Chaco War of 1932-1935 led many ranchers and landowners to abandon their lands in the active war zone between Bolivia and Paraguay, somewhat ironically, the war would also prove key in solidifying cattle ranching and other extractive activities that advanced the agricultural frontier in the Bolivian Chaco. For Indigenous communities and *mestizo* smallholders, however, the impacts of the war were far less favorable. Military occupation of the

Chaco region intensified the process of displacement and dispossession of Indigenous peoples and *mestizo* smallholders alike (Hirsch et al, 2021.). The Weenhayek people within the Pilcomayo basin and the Guaraní communities located in the municipal departments of Chuquisaca and Santa Cruz, whose territory was forcibly occupied by Bolivian troops during the war, are clear examples of the intensification of this process (Bazoberry Chali, 2003; Humphreys Bebbington & Cortes, 2021).

Even with the war's end in 1935, the occupation of Indigenous territory persisted, as sentiments surrounding the Chaco as Bolivian territory reinforced the Bolivian state's sense of fiscal entitlement to the land in the Chaco (Bazoberry Chali, 2003). Indeed, many soldiers remained in the Indigenous territory, such as that of several Weenhayek communities, and began practicing extensive cattle ranching that forced the Weenhayek to marginal land and stressed natural resources that the Weenhayek used (Humphreys Bebbington & Cortes, 2021). Despite the monumental role that Indigenous peoples of the Chaco and throughout Bolivia played in fighting for and assisting Bolivian soldiers, Indigenous peoples were excluded from voting since they were not recognised as citizens (McKay, 2020, p.34). For the Indigenous groups of the Chaco, Weenhayek, Tapiete, and Guaraní, their relative isolation in the eastern lowlands also made larger-scale organization with national peasant movements particularly challenging, and the Guaraní were even explicitly excluded from joining peasant labor unions (Guerrero Peñaranda, 2005).

The first agrarian reform of 1953 in Bolivia allowed large-scale ranchers and other large landowners to take advantage of certain mandates concerning land use defined in this reform to consolidate their land and prevent it from being redistributed (Guerrero Peñaranda, 2005). Rather paradoxically, agrarian reform over the last six decades has facilitated the expansion of the agricultural commodity frontier expansion and the consolidation of land in the hands of large-scale landholders (McKay, 2020). The implementation of the law has reinforced the importance of political networks and influence as a mechanism for securing access to land, generating a political structure built based on favors rather than equitable development in significant portions of the eastern lowland Chaco departments of Chuquisaca, Tarija, and Santa Cruz (Bazoberry Chali, 2003). As such, although 30% of the country's agricultural land was redistributed to approximately 200,000 Indigenous peoples and peasants in the altiplano and highlands of the country (McKay, 2020, p.34), the Indigenous peoples of the eastern lowlands regions were left without any benefits from this agrarian reform (Guerrero Peñaranda, 2005). In fact, this agrarian reform even created a new landowning social class that shifted into the eastern lowlands as a result of *la marcha al oriente* ("march to the east") that was incorporated into the agrarian reform plan from the Bohan Plan (Regalsky & Ortega Breña, 2010; McKay, 2020). Merwin L. Bohan, a US State Department official, proposed the eponymously named plan in 1942, and its implementation began in 1952 (McKay, 2020, p.35). The key component of this plant was the state's encouragement of migration to the eastern lowlands by offering generous amounts of land ranging from 20 to 50 hectares to the highland peasant class (Regalsky & Ortega Breña, 2010; McKay 2020). On the other hand, political and economic elites were offered considerably larger landholdings of 500 to 50,000 hectares (McKay, 2020, p.35).

Within just a few years after the first agrarian reform, other infrastructural and economic developments encouraged further growth in the region of the eastern lowlands, and especially in the basin of the Pilcomayo. The first wave of Mennonite colonists arrived in the Bolivian lowlands between 1954 and 1967, and in the last three decades, they have expanded into the region of the Pilcomayo basin (le Polain de Waroux et al., 2021). In 1974, a vegetable oil factory became functional in Villa Montes, and an irrigation project around the Pilcomayo carried out between 1989 and 1993 also piqued investors' interest in possessing land in the area (Bazoberry Chali, 2003). Additionally, a second agrarian reform took place in 1996 with the passing of Law 1715 (McKay, 2020, p.37). Although the language of this law intended to restore illegally expropriated landholdings to peasants and Indigenous peoples, in practice, the economic and political elites of the agribusiness sector effectively neutralized the intentions of this law in the eastern lowlands of Bolivia, including the region of the Chaco (McKay, 2020, p.37-38; Guerrero Peñaranda, 2005; Bazoberry Chali, 2003).

The rise of the Movimiento al Socialismo (MAS) political party, founded by now ex-President Evo Morales, and Morales' consequent rise to the presidency in 2003 led to a new period of agrarian reform. In 2006, Morales announced a new era of agrarian reform stemming from Law 3545, with the primary objectives of redefining the terms of expropriation unproductive landholdings to redistribute them more equitably and reforming the nation's institute of agrarian reform to increase transparency (McKay, 2020, p.43). However, especially in the lowlands of

Bolivia, the reform did not necessarily translate to the equitable redistribution of land. In fact, party leaders of MAS argue that one of the state's roles is to extract natural resources to generate capital that can be returned to the people (McKay, 2020, p.140). This extractivist mentality was always and continues to be extended to the soy industrial complex as well. Taking off in the 1990s, soybean production and cattle ranching were driven strongly by foreign capital in Bolivia (McKay, 2020, p.38), not unlike in the case of Bolivia's two international neighbors of the Pilcomayo basin. Like their Paraguayan counterparts, the Bolivian Mennonite colonies also greatly contributed to the development of soy production, leading to soy becoming the most important crop of the Bolivian lowlands (le Polain de Waroux et al., 2021). Particularly with respect to the soy market in the region, the economic interests of smallholders in the Bolivian lowlands are tied to those of the large-scale landowners to whom the smallholders rent their land in *partida* (contract farming) arrangements (McKay, 2020, p.62). Hence, these smallholders are still dependent on their land, but are alienated from its capacity to produce food that they can directly consume or sell. Smallholders do not have the structural and relational mechanisms of access to technology, financial capital, and political power that have allowed the larger-scale enterprises to engage in soy commodity production (McKay, 2020, p.131).

3.5. Access to natural resources in the Pilcomayo and the Gran Chaco

In the Gran Chaco as a whole, various structural and relational mechanisms of access have aided the expansion of the agricultural frontier and explain the shifts in power that have defined who has gained, controlled, and maintained access to what resources at different points in time. Access to infrastructure, land, capital, credit, technology, and production and social networks facilitated agricultural expansion in the Gran Chaco driven by national pioneers, populating the Gran Chaco from other regions within the country, as well as by foreign investors (le Polain de Waroux et al., 2018). As discussed in Section 3.4.1, investors' perceptions of the region of the Argentine side of the Pilcomayo as a viable area for agricultural expansion was partly predicated on the increased accessibility of the region after the completion of Road 81. These mechanisms translate to greater financial power and political influence, allowing the actors who possess such power and influence to purchase and convert more land for commodity-driven agriculture.

This process has the effect of reducing the access of smallholders to land and natural resources. Even if some resources remain after conversion, these resources are often enclosed within the confines of private landholdings, rendering them inaccessible to rural populations (Altrichter & Basurta, 2008). For instance, a formerly communal source of surface water may become enclosed by fences, effectively removing rural populations' access to a viable surface water resource. Additionally, when minimally disturbed areas of the Gran Chaco are converted to large-scale intensive agriculture, the spatial distribution of the resources that rural populations rely on is reduced and fragmented, increasing the likelihood of local land conflicts and the risk of overexploiting the common-pool resources that remain (Seghezzo et al. 2011). The presence of large landholdings that practice agriculture and large-scale cattle ranching also further exacerbate the scarcity of viable water resources–both surface and subterranean–because of the large quantity of contaminants that enter into the surface water from livestock feces and agrochemicals that are sprayed on fields (Biocca, 2021; Correia, 2020).

Aside from the direct livelihood implications, reduced access to natural resources can weaken the social networks between community members as well (del Giorgio et al., 2022). This is of particular concern considering that mobilization against the encroachment of powerful agribusinesses requires a well-coordinated, organized response, but if the people affected are in conflict, such a response becomes even less likely to materialize. In fact, communities may even find themselves divided between those who support the influx of large-scale agriculture and those who challenge it (del Giorgio et al., 2022). In the most dire circumstances, the process of frontier expansion has led to the direct displacement of Indigenous peoples and smallholders from rural areas into urban areas as casual workers (Cáceres, 2015).

Despite the enormous challenges that the agricultural frontier presents, there are many examples of rural communities in the Chaco overall who have fought and continue to actively resist the encroachment of agribusinesses. Such communities have mounted Indigenous and peasant movements at the highly local to the international scale, in order to confront the systems that threaten their livelihoods (Alcorn et al., 2010; Cáceres, 2015; Gordillo & Leguizamón, 2005; Paz, 2020; Paz & Jara, 2020). In some cases, rural smallholders have themselves mounted fences to secure some of the resources that they rely on as a pre-emptive strategy to deter agribusiness investors from land grabbing and to signal occupation of the land (Paz, 2020). In the municipality of Figueroa in Argentina, a majority rural area located in the Gran Chaco, some rural smallholders enclosed communal resources with the support of local land boards and municipal institutions (Paz & Jara, 2020). Paz (2020) refers to these enclosures as "institutional architecture" that undermines the external threat that agricultural expansion poses and establishes clearly defined boundaries that impede outsiders' attempts to usurp access to these common-pool resources. This is one innovative path of resistance to external forces that some rural communities have successfully pursued.

However, the empirical case that Paz (2020) examines functions only for a particular set of circumstances. First, the common-pool resources of interest need to be stationary (such as trees and stable water reservoirs) or require a very small roaming area. Second, the enclosed area containing the resources the community requires access to must be sufficiently large to support everyone in the community. Finally, this strategy requires structural mechanisms of access to other resources that are necessary to mount the enclosure. The likelihood that all of these circumstances would be met in the majority of cases seems rather slim considering that most rural smallholders and Indigenous communities are relatively poor and the majority practice livelihoods that require extensive, open space. Moreover, for those populations who practice hunting as an important means of sustaining themselves, fences, depending on their material and height, are simply an obstruction, as their fragmentation of the landscape hinders wild animals' mobility (Xu et al., 2021). Moreover, if fencing only takes place at smaller household units but without universally fencing the areas of all homes in the community, tensions between those with fences and those without may rise due to conflicting perspectives around communal land and resources (del Giorgio et al., 2022). Therefore, in general, the enclosure of the commons is carried out by external actors seeking to maximize economic profits in the agricultural sector and occurs against the will of the rural populations who require these common-pool resources to maintain their livelihoods (Cáceres, 2015).

Finally, the process of privatization in the Gran Chaco and, consequently, the reduction in areas that are *de facto* open-access demonstrate why structural and relational mechanisms of access are often vital to securing everyday access to resources despite whatever formal rights-based mechanisms of access may technically be in place. In Paraguay, Article 64 of the Paraguayan Constitution states that Indigenous communities of the country have the right to access land they have traditionally occupied for the "conservation and development of their particular livelihoods". Paraguay's Law 904/81 further articulates this right in the articles of Chapter II. However, Glauser (2018) details that the Indigenous Angaité community members of the colony of La Patria in the Paraguayan Chaco are expected to secure permission from ranch owners occupying Indigenous land to access land to hunt, gather geographically native food sources, and fish. Despite the *de jure* rights that Indigenous peoples possess to access these resources, the lack of enforcement of the laws that theoretically protect these rights do not reasonably enable the *ability* to benefit from the essential resources. Instead, access is negotiated through the power differential between Indigenous peoples and the ranch owners who dictate who gains access to the resources on the land the ranch occupies (Correia, 2021). For example, in order to secure access to the resources necessary to support their livelihoods, some Angaité community members have adopted the strategy of directly working on these ranches as wage laborers (Glauser, 2018). This is just one example of many strategies that rural populations have adopted to secure access to resources that support their livelihoods in response to the advancing commodity frontier, resulting in the generating and redefining of relational contexts. Nevertheless, the spatial and temporal availability of the resources eventually diminishes, and changes in management at the ranches can generate unfavorable conditions of negotiation for workers (Glauser, 2018). The rapid evolution of the agricultural commodity frontier generates considerable instability and uncertainty for rural populations attempting to secure access to resources, and Indigenous communities and smallholders must often adopt multiple strategies of securing access simultaneously and find new avenues of access frequently.

3.6. Chapter conclusion

The contextual factors surrounding the Gran Chaco and within the basin of the Pilcomayo that I described in this chapter are key to understanding the interwoven issues of surface water availability and surface water access. To begin the discussion, I discussed the inseparable intersection of the Pilcomayo basin's hydro-geomorphological attributes and the geopolitical circumstances that shape the hydrosocial territory. I then transitioned into discussing the availability of surface water across the region and how this corresponds to its use by the Indigenous peoples and mestizo smallholders who live in the basin. Next, I moved into a review of the evolution of the agricultural frontier in the three countries (Argentina, Paraguay, and Bolivia) that the basin traverses. Finally, I provided an overview of the issues surrounding access to natural resources in the Pilcomayo basin and across the Gran Chaco as a whole. Now, having set the stage with this discussion of the regional context of this study, I now move into a discussion of the methodological approaches that I applied to analyze the intersection between surface water distribution, the expanding agricultural frontier, and rural populations' access to surface water in the Pilcomayo basin.

CHAPTER 4. METHODOLOGY

Our first objective in this study was to broadly understand what the distribution of different types of surface water looks like across the Pilcomayo basin. To understand how surface water varies across the landscape of the basin, I generated a classification of surface water according to spatial-temporal characteristics developed in two main stages: image segmentation and classification of surface water according to spatial extent and frequency of saturation along with surface water source size. Although not *all* surface water sources can sustain every type of rural livelihood, especially in the case of fishing, I assume that all surface water within the classification is useful, albeit to varying degrees, to either directly or indirectly support at least one rural livelihood practiced in the region. With this livelihoods-centered approach in mind, the first step in the characterisation of surface water entailed performing an image segmentation on monthly surface water detection data from the GLAD Surface Water Dynamics dataset (Pickens et al., 2020) in Google Earth Engine (EE) in order to generate distinct objects representing different surface water sources based on their spatial contiguity and their long-term temporal behaviour over the full 21-year period. Then, for each object, I generated two indices: one based on the object's average surface area covered with water and the other representing the average number of months in which the object held any amount of water in the full time period. Finally, I used the sample mean of each index value as the threshold to define four surface water classes representing the saturation extent and saturation frequency (which, together, the spatial-temporal stability) of the objects. I then added a size criterion, calculated by extracting the absolute surface areas of the objects, to generate the final set of 12 classes representing surface water in the region.

I use the results of the surface water classification as inputs to accomplish the second objective of this study: to assess how access to the different classes of surface water is changing as the agricultural frontier expands across the landscape. The access analysis involved three main steps: (1) generating annual rasters representing accessibility of the landscape, in which areas converted to agriculture (either cropland or pastures) are considered completely inaccessible and given a “no data” value, while areas of natural vegetation completely accessible and given a value of 1; (2) calculating the shortest distance from surface water objects of each class across the whole area, using a cost distance algorithm with surface water objects as the starting points and the accessibility rasters as the cost surfaces; and (3) extracting these distance values at the point-based locations of settlements to. The extracted distance values represent the distance that people in each of the settlement locations need to travel in each year to reach the nearest source of surface water within each of the 12 classes. I used these values to demonstrate the annual and total change in distance to surface water between the years 2000 and 2020, a time period during which agricultural expansion accelerated.

The access analysis focuses solely on the Dry Chaco subregion within the basin. In the proceeding sections, I describe the data sources I used, the scale and scope of the analyses, the specific methods I applied to execute the surface water classification and access analysis. Figure 4 shows the workflow for the full analysis.

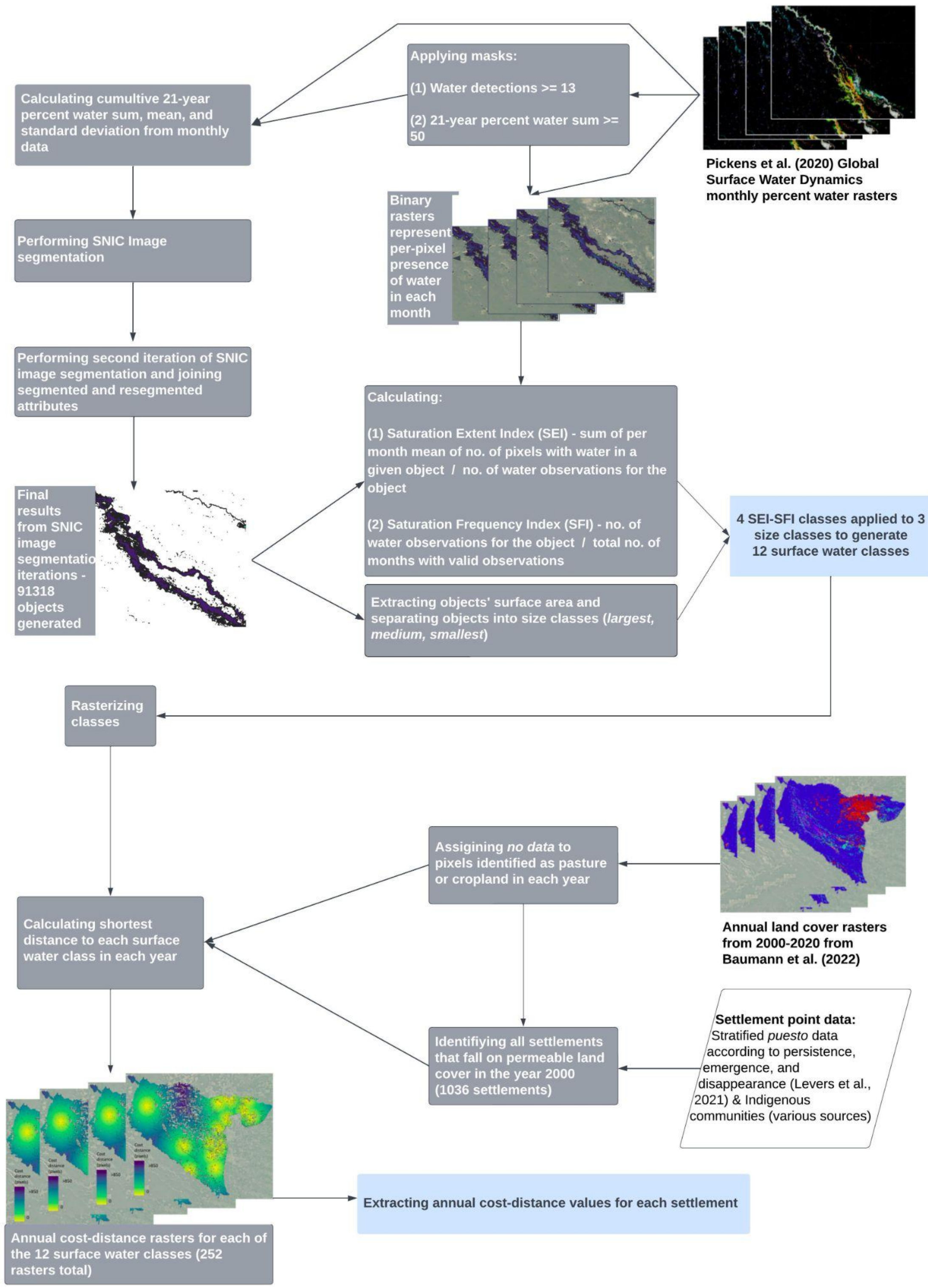

Figure 4. Workflow outlining the stages of the full analysis, starting with the spatial-temporal classification of surface water sources in the upper half and the access analysis in the lower half. See Table 4.5 for descriptions of each of the variables in the surface water classification.

4.1. Sources of data

I used Pickens et al's (2020) Global Surface Water Dynamics (GSWD) dataset to generate objects representing sources of surface water and the variables used to classify these objects according to their spatial-temporal attributes. In the GSWD dataset, surface water is represented as a percent describing how often water was detected in a given pixel for a particular month of a specific year in Landsat imagery at 30 meter resolution between the years 1999 through 2022. The monthly surface water data from this dataset was used to extract a total of 250 months (two months in the dataset had null values and thus were excluded) covering the 21-year period of interest from 2000-2020. The GSWD dataset served as the ideal source of data for the analysis considering the reliability of its monthly data and its time period overlapping with a period during which the region of the Pilcomayo was experiencing rapid land use changes (le Polain de Waroux et al., 2018).

While the GSWD dataset was key to generating the objects representing surface water and the variables used to generate the surface water classes, I employed several other datasets to identify surface water, delineate the boundaries of the basin, and exclude areas above 375-m in elevation. Table 4.1 outlines the other data used at different stages of the classification of surface water.

The results of the classification analysis served as the starting points in the cost distance calculation assessing the changes in rural populations' access to surface water sources over the period of 2000 to 2020. I used land cover/use data from Baumann et al. (2022) to determine annual changes from (semi-)natural land cover classes to agriculture (cropland or pastures) and sourced the locations of settlements that rural populations occupy from several datasets. *Puestos* (homesteads) throughout the region were provided by Levers et al., (2021), who produced digitized point data representing the location of *puestos* in the Gran Chaco between the years 1985 and 2015. In this dataset, both *mestizo* smallholder and Indigenous smallholder *puestos* were mapped using high resolution imagery available in Google Earth and Landsat. The authors identified the persistence, emergence, and disappearance of these *puestos* from 1985 to 2015 as well as from 2000 to 2015. The *puesto* point data was used to identify the locations of rural populations whose access to surface water I consider in this chapter. Only the point data representing the persistence, emergence, and disappearance of *puestos* for the period between

2000 and 2018 were incorporated, as this time frame falls within the one considered in the characterisation of surface water (from 2000 to 2020).

Data	**Description & Purpose**	**Source**
GLAD Global Surface Water Dynamics (GSWD) dataset (Pickens et al., 2020)	Represents surface water as a percent based on how often water was detected in a given pixel for a particular month of a specific year in Landsat imagery between the years 1999 through 2022. Used to generate objects representing surface water sources and the variables used to classify these objects according to their spatial-temporal attributes.	glad.umd.edu/dataset/global-surface-water-dynamics
The USGS and National Geospatial Intelligence Agency's (NGA) Global Multi-resolution Terrain Elevation Data (GMTED 2010)	Used to exclude areas within the Chaco portion of the Pilcomayo basin that were >375 meters above sea level at 30 arc seconds.	usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-multi-resolution-terrain-elevation
HydroSHEDS: (1) HydroSHEDS Basins (Lehner & Grill, 2013; Lehner et al., 2008) (2) MERIT Hydro Supplementary visualization Layer (Yamakazi et al., 2019) & HydroSHEDS Basins Level 12	The HydroSHEDS Basins database was developed by Lehner & Grill (2013) and Lehner et al. (2008). The Level 12 data consists of the small scale of nested, hierarchical sub-basins, so these were used to demarcate the boundaries of the Pilcomayo basin. The MERIT Hydro dataset is a map that represents the flow direction of rivers and streams based on the MERIT DEM elevation data as well as water datasets from G1WBM, GSWO, and OpenStreeMap. Used to delineate the boundaries of the Pilcomayo basin.	Available in GEE catalogue: (1) "WWF/HydroSHEDS/v1/Basins" (2) *ee.Image("MERIT/Hydro_reduced/v1_0_1")*
WWF's Terrestrial Ecoregions of the World (Olson et al., 2001)	Provides shapefiles that identify biomes across the planet. Used to delineate the Dry Chaco and Humid Chaco subregions of the Gran Chaco.	https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world

Table 4.1. A breakdown of the data used for the surface water classification.

The locations of Indigenous communities were determined using a variety of sources Argentina's Instituto Nacional de Asuntos Indígenas (INAI) *Mapa de pueblos originarios*[3]; Bolivia's Instituto Nacional de Reforma Agraria (INRA) *Tierras Comunitarias de origen (TCO) tituladas por el Instituto Nacional de Reforma Agraria*,; and Paraguay's Instituto Nacional de Estadística (INE)

[3] Data available at *Pueblos Originarios*.

Atlas de Comunidades de Pueblos Indígenas en Paraguay[4]. Because some of the data from INAI and INE indicated that there were communities in areas that did not show visible signs of permanent human settlements, I manually excluded some communities from these sources if Google Earth Satellite imagery did not offer sufficient evidence of permanent human occupation.

4.2. Geographic scale and scope of the study area

The surface water classification analysis covers a narrow northwest portion of the Pilcomayo River basin in Bolivia and the full area of the alluvial fan within the region of the Chaco plains that extends across Argentina and Paraguay. This area includes the Dry Chaco in the west and the Humid Chaco in the east. In total, the Dry Chaco subregion covers a surface area of ~109,408 km^2 while the Humid Chaco covers an extent of ~82,477 km^2. Because higher elevation regions have different surface water dynamics that cannot be generalized in the same way as the areas in the flat Chaco plains region of the basin, I removed areas at an elevation of >375m above sea level using the GMTED2010 DEM. This resulted in the exclusion of areas east and west of the upper northwest portion of the river in Bolivia. Figure 4.2A shows the boundaries of the areas within each country and within the Dry and Humid Chaco that fall within the region of study.

The access analysis takes place within the portion of the basin that falls within the Dry Chaco, which forms 57% of the basin's surface area. I excluded the Humid Chaco from the access analysis since the frequent flooding in the region obfuscates interpretation of land cover types. Additionally, the Dry Chaco is where the agricultural commodity frontier's expansion has been most pronounced, and one can more reliably discern the different land cover types of the Dry Chaco in satellite imagery at 30 meter resolution. In this subregion, the dry season also tends to be more severe, resulting in higher physical scarcity of surface water and, consequently, greater challenges in finding both physically available *and* accessible surface water sources.

[4] Data available at ine.gov.py.

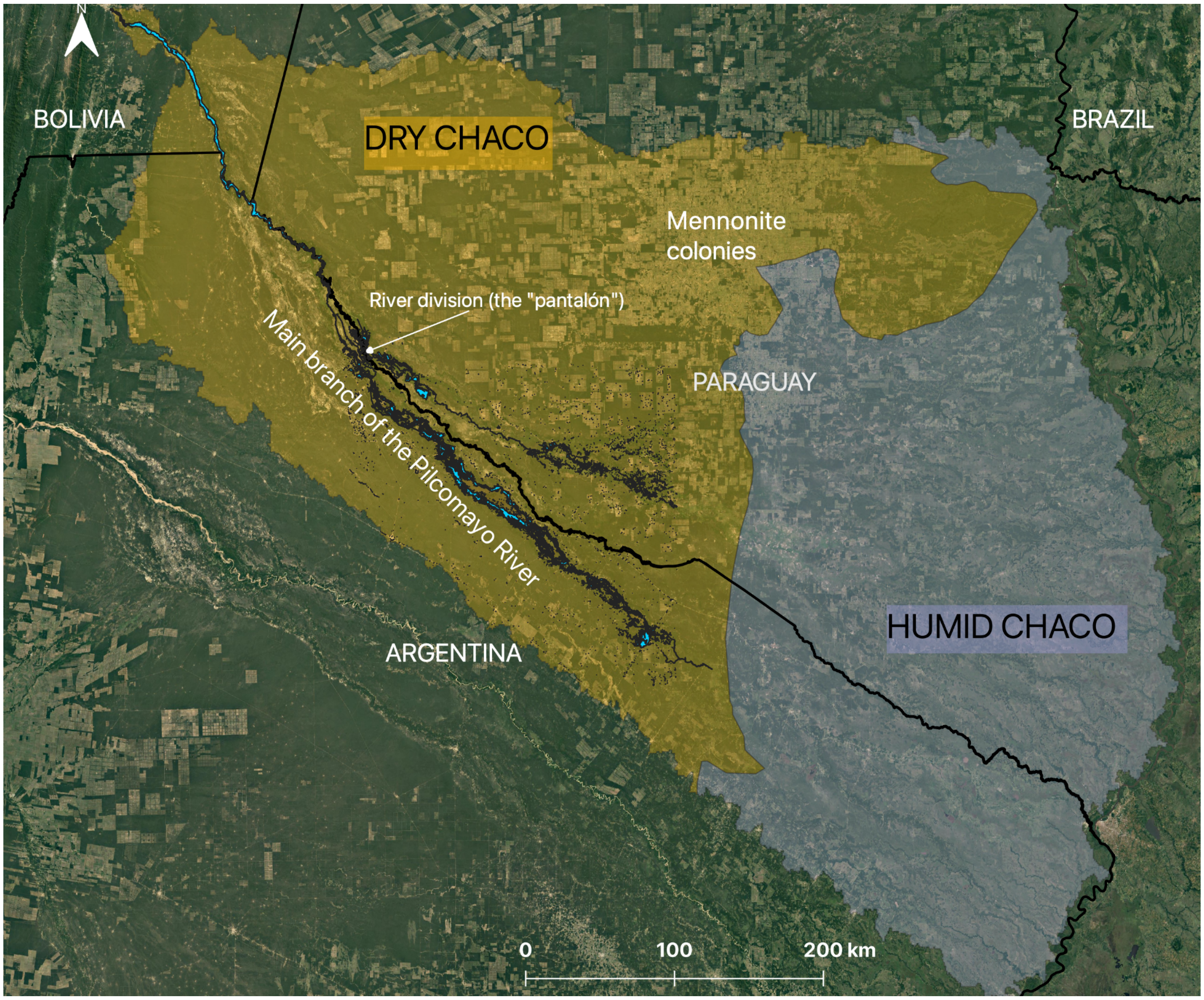

Figure 4.2A. A view of the full region of study for the surface water classification with the climatic boundaries of Dry Chaco and Humid Chaco as well as the country boundaries of Argentina, Paraguay, and Bolivia delineated.

The settlements within the Dry Chaco are concentrated along the Pilcomayo River, though there are a few clusters of settlements located beyond the floodplain of the river in regions in the northeast corner, Central Chaco, and northwest. There are four different settlement types, three of which (*disappearing, emerging,* and *persisting*) are from Levers et al.'s (2021) classification of the *puestos* that they identified. Figure 4.2B shows the spatial distribution of the four settlement types within the Dry Chaco. The settlements sum to 1036, and they are classified as follows:

1. *Disappearing* - A total of 133 *puestos* that were present at some point in the time period but were abandoned by the year 2018.
2. *Emerging* – A total of 60 *puestos* that were not present in the year 2000 but appeared at some point before 2018.
3. *Persisting* – A total of 741 *puestos* that were present during the full time period (up to the year 2018).
4. *Indigenous* – A total of 102 Indigenous communities (no temporal data for these; collected from various data sources as described in the previous section).

In terms of the temporal scope of the study, I focus on the 21-year period of 2000 to 2020 for both the classification of surface water and the subsequent access analysis. I characterize surface water over the broad scale of the full 21-year period rather than breaking the period into parts since there were no significant changes to the region's topography across this period, and most natural surface water sources located beyond the floodplain of the Pilcomayo river remained relatively hydrologically stable. Even in focusing at the level of Pilcomayo and its floodplain, most of these sources experienced their greatest spatially consequential changes to their hydrology prior to the year 2000. The bifurcation of the river through the Proyecto Pantalón took place in the 1990s (Brown et al., 2018), while the river's southeast shift from Paraguay to Argentina began in the 1940s and resulted in the drying of the the wetland Patiño in Paraguay by the early 1980s (Baumann & Cavallaro, 2008; Lamenza et al., 2019). In addition, the longer-scale period allows sources with lower frequency of saturation to be captured by the classification.

In the access analysis, the stratification of the *puesto* data (by *disappearing, emerging*, and *persisting*) allowed us to identify whether there is any correlation between the persistence, emergence, and disappearance of rural populations and the temporal changes in access to surface water. I treated Indigenous communities as a single group without temporal differentiation since data regarding their years of emergence or disappearance were not available. Consequently, in this analysis, I assumed that all Indigenous settlements were present for the full time period.

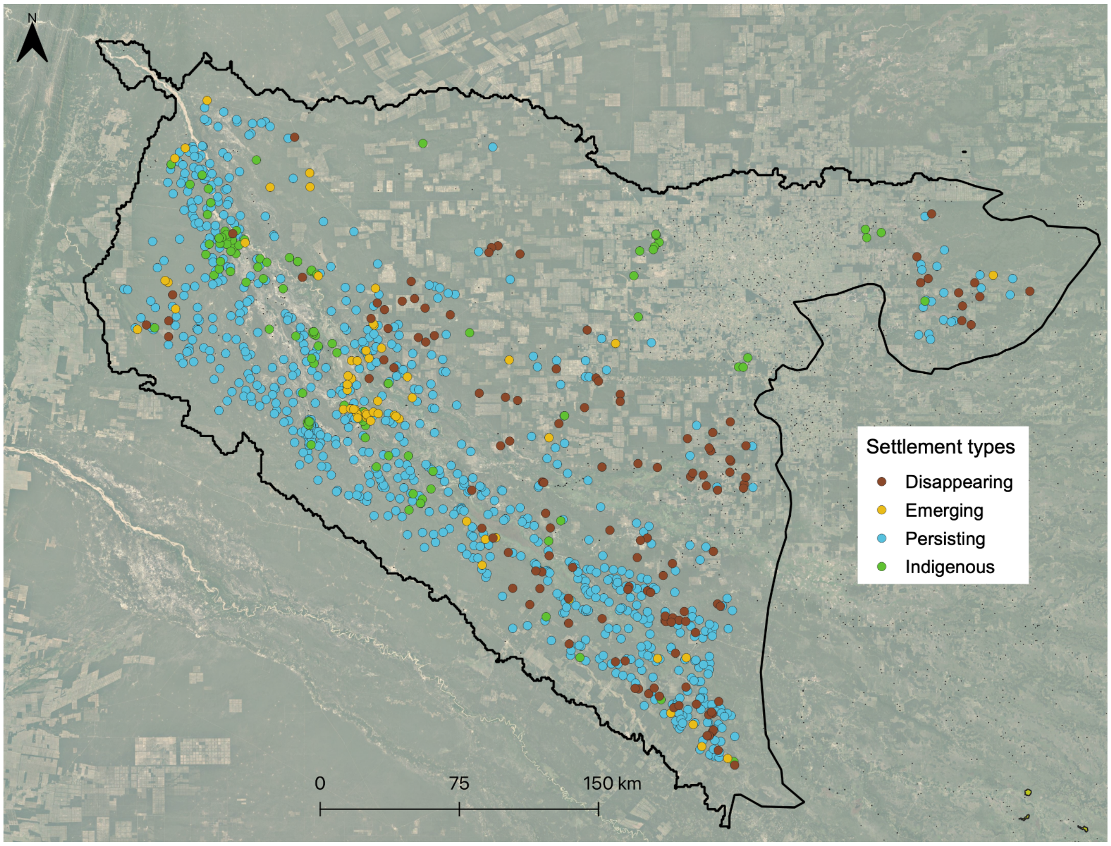

Figure 4.2B. The spatial distribution of the four settlement types (data from Levers et al. [2021], Argentina's INAI, Bolivia's INRA, and Paraguay's INE) in the Dry Chaco portion of the basin.

4.3. Creation of objects representing surface water sources

Image segmentation is a process by which pixels are aggregated and divided to form objects that offer a more logical representation of distinct features in the region represented in the image. The process groups pixels that resemble one another into objects according to a set of user-specified parameters. Here, I use simple non-iterative clustering (SNIC), a segmentation method that prioritizes the connectivity of pixels (Achanta & Süsstrunk, 2017) to ensure that pixels are grouped based on their spatial contiguity relative to one another. Additionally, SNIC image segmentation does not require multiple k-means iterations, reducing the computationally intensive demands of alternative segmentation algorithms that rely on iterative processing (Achanta & Süsstrunk, 2017). The SNIC image segmentation algorithm in Earth Engine has been used in various other studies identifying land use and land cover in geographically and climatically diverse regions. Ghorbanian et al. (2020) applied Earth Engine's algorithm to generate high-accuracy land cover maps of Iran for the years 2017 and 2019 based on data from Sentinel-1 and Sentinel-2. In their study with even greater geographic proximity to my region of study, Paludo et al. (2020) used the algorithm to produce maps of 90% accuracy identifying soybean and corn agricultural plots in the Brazilian state of Paraná with imagery from Landsat, Sentinel-2, and NASA's Shuttle Radar Topography Mission (SRTM).

In Earth Engine, the SNIC segmentation outputs the per-object mean of each input band and generates a new band containing the unique IDs for each object. In an initial round of image segmentation, I used the 21-year sum, mean, and standard deviation of each pixel's percent water value as temporal variables by which to group pixels. The percent water sum represents the cumulative percent water across the 21-year period of interest. This variable provides insight into the pixels that have held the highest amount of water in the full time period. The percent water sum and the mean of percent water for a given pixel together offer insight into the frequency with which the pixel tends to hold water over the 21-year period. Finally, the standard deviation elucidates the overall consistency or irregularity of water recurrence. For instance, a pixel with a high total sum, relatively low mean, and high standard deviation suggests that there may have been many months in which water was always or nearly always detected, yielding a high percent water value, but there were also several months in which there was little to no water detected. Pixels with a high sum and mean percent water with a relatively low standard deviation are more likely to have consistently held water throughout the time period, making them more temporally stable.

I applied two masks to the input images used in the segmentation to reduce the impact of residual detection errors in the GSWD dataset on the segmentation. For both masks, I set their threshold values as low as reasonably possible since the natural hydrologic variability of the region could result in low levels of saturation. For instance, in the case of the Pilcomayo river itself, its meandering in conjunction with seasonal flooding mean that water is likely to flow in and out of pixels depending on the time of year as well as the year itself, as the river channel has changed between over the past two decades.

The first mask eliminated pixels with fewer than 13 months (consecutive or nonconsecutive) with a recorded percent water value >0. I considered this a reasonable minimum number of valid detections since it ensures that only pixels that were present for at least 5% of the time period were included in forming the objects. This mask also significantly reduced the presence of artifacts associated with clouds and the Landsat 7 scan line errors in the dataset.

The second mask required that the included pixels' 21-year percent water sums be >= 50 (i.e., that there be at least one month at 50% water, or two or more months within the 21-year period that sum to 50%). As in the case for the first mask based on the number of detections, the minimum sum and mean percent water masks were selected based on visual inspection and my determination of what constitutes a reasonable minimum for the region to reduce error without overly excluding potentially valid objects representing true sources of surface water.

With these masks applied, I carried out the first round of segmentation. This first round of results was exported at 30 meter resolution in order to capture the detailed shapes of small surface water sources. At this higher resolution, however, the algorithm over-segmented larger objects such as rivers. To unify these larger objects, I conducted a second segmentation of the first-round results, in which the objects produced in the first round were set as the seeds from which the new objects should be produced, introduced a size parameter instructing the algorithm to maintain contiguity of the large objects captured at the 150-m scale, and exported the result at this scale. I then combined the first-round results (which captured the smaller objects) and second-round results (which maintained the contiguity of larger objects) in order to create the final set of objects.

4.4. Creation of indices to capture different types of surface water

I aimed to sort the individual objects formed in the segmentation stages into classes that broadly capture the spatial-temporal tendencies of surface water in the region. Using the Pickens et al., (2020) monthly percent water data, I extracted binary rasters representing the presence of surface water in each pixel for each of the 250 months in the time period. I then formed two indices to represent the spatial-temporal stability of the objects: the *saturation extent index* (*extent*) and the *saturation frequency index* (*frequency*).

The *frequency* represents how often a given object holds water - i.e., how often is the object not dry. It was calculated as the total number of months with water, excluding invalid observations[5], for the object across the full time period, divided by the total number of months with valid observations (whether with water or not). The *extent* represents the percentage of a given object's surface area that is covered with water on average when that object does hold water - i.e., when the object is not dry, how saturated is it. To calculate it, I represented the monthly saturation extent at the object level as the number of pixels with surface water observations divided by the total number of pixels in the object. I then formed the *extent* by summing these monthly extents for each object and dividing this value by the total number of months with valid monthly water observations for the object across the full time period.

4.5. Classification of surface water

I calculated the mean extent and the mean frequency across all of the objects to generate respective thresholds for the extent and frequency classes, defining the class as *high* if above the respective mean for the given index and as *low* if below. Combined, the saturation extent and saturation frequency indices form the basis for the *saturation classes*. The saturation classes encompass both spatial and temporal attributes of objects in their simultaneous consideration of both the relative saturation extent (i.e., the monthly ratio of the number of pixels composing the object that held water to the total number of pixels composing the object) and the frequency with which different levels of saturation extents were reached (i.e., the number of months in which the object held water at any spatial extent).

In addition to the saturation classes, the size of the objects can greatly impact their dynamics. The large and small objects can have disproportionate advantages and disadvantages because of their size. For instance, in the case of the small objects, the reduced spatial extent of potential saturation could favor reaching a high extent value since fewer pixels are factored into the ratio of saturated pixels to total pixels composing the object. Yet if any of the few pixels composing the object experiences a dry month, the object is also more likely to fall into the lower thresholds of saturation extent than the larger objects. The inverse is true for the large surface water sources

[5] Invalid observations were pixels with < 13 months (consecutive or nonconsecutive) with a recorded percent water value > 0.

of the region: any number of dry pixels will not impact the frequency value, but their impact will be reflected in the extent value. Since size differentiation influences other attributes of surface water, to facilitate the interpretation of the classification I grouped objects into three size classes based on the quartiles of absolute surface area: large (third quartile and higher), medium (between the first and and third quartiles), and small (first quartile and lower). When taken together, the saturation classes and the size classes form what I refer to as the *surface water class*. I explain each of the variables required to arrive at this final classification in Table 4.5.

After obtaining the classification results, I binned the surface water classes into a 10x10 km grid to generate density maps (figure 5.2A through figure 5.2C). I also generated a map representing the probability of encountering a specific surface water class based on a random sample of 75,000 points across the full region (figure 5.2E). These maps served as visualizations of the distribution and frequency of the 12 classes and are displayed and discussed in Chapter 5.

Stage of analysis	Variable	Description & Purpose
Image segmentation	Percent water sum, mean, & standard deviation	Used as the temporal variables that informed the image segmentation algorithm's aggregation of spatially contiguous pixels into objects.
Spatial - temporal classification of objects	Saturation Extent Index (extent)	The ratio of the sum of per month mean number of pixels with water in a given object to the number of water observations for the object. Represents the relative mean saturation extent of an object throughout the full time period (i.e., the mean relative surface area covered with water for an object within the full time period). $SEI = \frac{\sum \overline{X_i}}{W}$, $i = 1, 2 \ldots k$ Where: X_i = percent pixels with water for given month W = Number of months with any amount of water for the object k = Months
	Saturation Frequency Index (frequency)	The ratio of the number of water observations for the object to the total number of months with valid observations whether with water or not. Represents the relative frequency of saturation (i.e., how often an object holds water). $SFI = \frac{W}{T}$ Where: W = Number of water observations for the object T = Total number of months with valid observations in full time period
	Saturation classes	4 classes representing the extent and frequency combined. They are defined as follows: *1. High extent - High frequency* *2. High extent - Low frequency* *3. Low extent - High frequency* *4. Low extent - Low frequency* Objects >= the mean extent or frequency are classified as *high* for the respective index. Objects with < the mean extent or frequency are classified as *low* for the respective index.
	Size classes	Three size classes were defined (*large, medium, small*) in order to apply the extent and frequency classes to each of the size classes.
	Surface water classes	12 classes representing the spatial-temporal attributes of surface water sources. They are written with the size class and then the saturation class (large high extent - high frequency, medium high extent - high frequency, small high extent - high frequency, large high extent - low frequency, medium high extent - low frequency, etc.)

Table 4.5. The variables used to generate the final surface water classes. The variables are grouped according to the stage of the analysis in which they were used (either the segmentation or the spatial-temporal classification) and are described according to their source and their purpose in the analysis.

4.6. Analysis of changing distances from settlements to surface water

To determine how access to water sources of different classes has been changing over time, I used a simple cost distance algorithm in QGIS with the GRASS *r.cost* algorithm to calculate the shortest distance from the nearest surface water source of a given surface water class to any point within the region of study. Cost distance analyses often consider additional variables such as the presence of roads or footpaths and elevation. However, for the purposes of this analysis, I used the cost distance algorithm to calculate straight-line distance, as this serves as an appropriate approximation for comparing changes in distance to surface water over time.

To represent the inability of smallholders to access resources enclosed in private properties or to transit through these properties, I considered all pixels under pasture or agriculture as inaccessible and assigned them a "no data" value. Conversely, I considered all pixels corresponding to natural vegetation in Baumann et al. (2022) (including woodlands, natural grasslands, palm savannahs, wet grasslands, and all other types of semi-natural vegetation) as accessible and assigned them a value of 1 that was converted to km after the cost distance operation had run. I used the land cover class "disturbed woodlands" as an accessible land cover type as well, as visual inspection indicated that these areas do not generally correspond to the clearing of land for agriculture. I also include large and mid-size towns such as Filadelfia, Mariscal Estigarribia, and Ingeniero Juárez as accessible in the cost raster based on the assumption that any source of surface water located in an urbanized area constitutes a publicly-available source. Nevertheless, these represent less than 1% of the total accessible area in both the years 2000 and 2020.

I excluded individual settlements that did not contain any sources of surface water of a given class within a 15 km radius, based on two assumptions: (1) 15 km is likely the maximum range that the livestock kept by rural populations would travel for water on a daily basis (del Giorgio et al., 2021), hence, (2) water geographically situated more than 15 km from a settlement is not readily accessible from that settlement to begin with. As a result, the number of settlements varied in the consideration of each surface water class. I then extracted the distance values to each surface water class for each settlement identified in the region. Increases in distance (in km) over time indicate either: (1) an increasing area of cropland/pasture that people in a given settlement would need to avoid if travelling to the nearest surface water source of a given class, or (2) an increasing number of sources falling within agricultural/ranching landholdings. In addition to increasing change in distance, I also examine the proportion of settlements that maintain access to specific types of water objects within a 15 km distance over time, as a way to represent changes in access over time.

Finally, over time, some settlements become enclosed in agricultural areas, which means that distances could not be calculated for the year 2020. To deal with this issue, I excluded these settlements from the analysis when looking at changes in distances to water sources, and instead looked at the difference in distance for each water class between the first year and the year that this settlement became enclosed.

4.7 Chapter conclusion

In this chapter, I outlined the sources of data that I used and explained the spatial and temporal scales of my analysis. I then discussed the process of creating objects that represent surface water sources through the segmentation, indices that represent spatial-temporal attributes of water most pertinent to livelihood-based use, and a classification of surface water based on the indices. Finally, I explained how I used the cost-distance algorithm to calculate annual distances from settlements to surface water during the time period of 2000 to 2020. In the next chapter, I will present the results from the stages outlined in my methodology.

CHAPTER 5. RESULTS

Using the objects formed from the segmentation, I generated the 12 classes of surface water to examine how distribution of surface water and the expansion of agriculture in the Pilcomayo basin define the conditions of rural populations' access to different types of surface water. I assume that the surface water sources that I classified are static in their classification throughout the 21-year period, though with the understanding that this may not be universally true for all the surface water sources included in the analysis. I also frame *access* in terms of a settlement's distance, in km, to a given surface water source of the class of interest; that is, an increase in distance suggests a decrease in access. Since three of the four settlement types were defined by their temporality (*disappearing, emerging*, and *persisting*), my analysis also served to show whether the disappearance, emergence, and persistence of settlements correlates to their geographic proximity and access to surface water types that likely have a higher capacity to support livelihoods. In the sections that follow, I outline the findings of the surface water classification and subsequent access analysis.

5.1. Surface water classes produced

The segmentation iterations and post-segmentation processing resulted in the formation of 85,930 objects. Figure 5.1A displays the results from these stages, and from this two general patterns emerge. First, there is a sparser distribution of surface water objects in the Dry Chaco subregion, particularly in the small area southwest of the upper branch of the Pilcomayo river, the area north of the river's "pant legs" division, the area between the branching "legs" of the river, and the area south of the widest portion of the river. In fact, despite the Humid Chaco subregion covering 43.0% of the entire basin (14.0% less surface area than the Dry Chaco), it holds 53.9% of the *large*, 52.3% of the *medium*, and 57.7% of the *small* objects in the region. Nevertheless, there appears to be a relatively lower density of objects represented in the northeast corner of the basin compared to the density seen in the other areas within the Humid Chaco subregion.

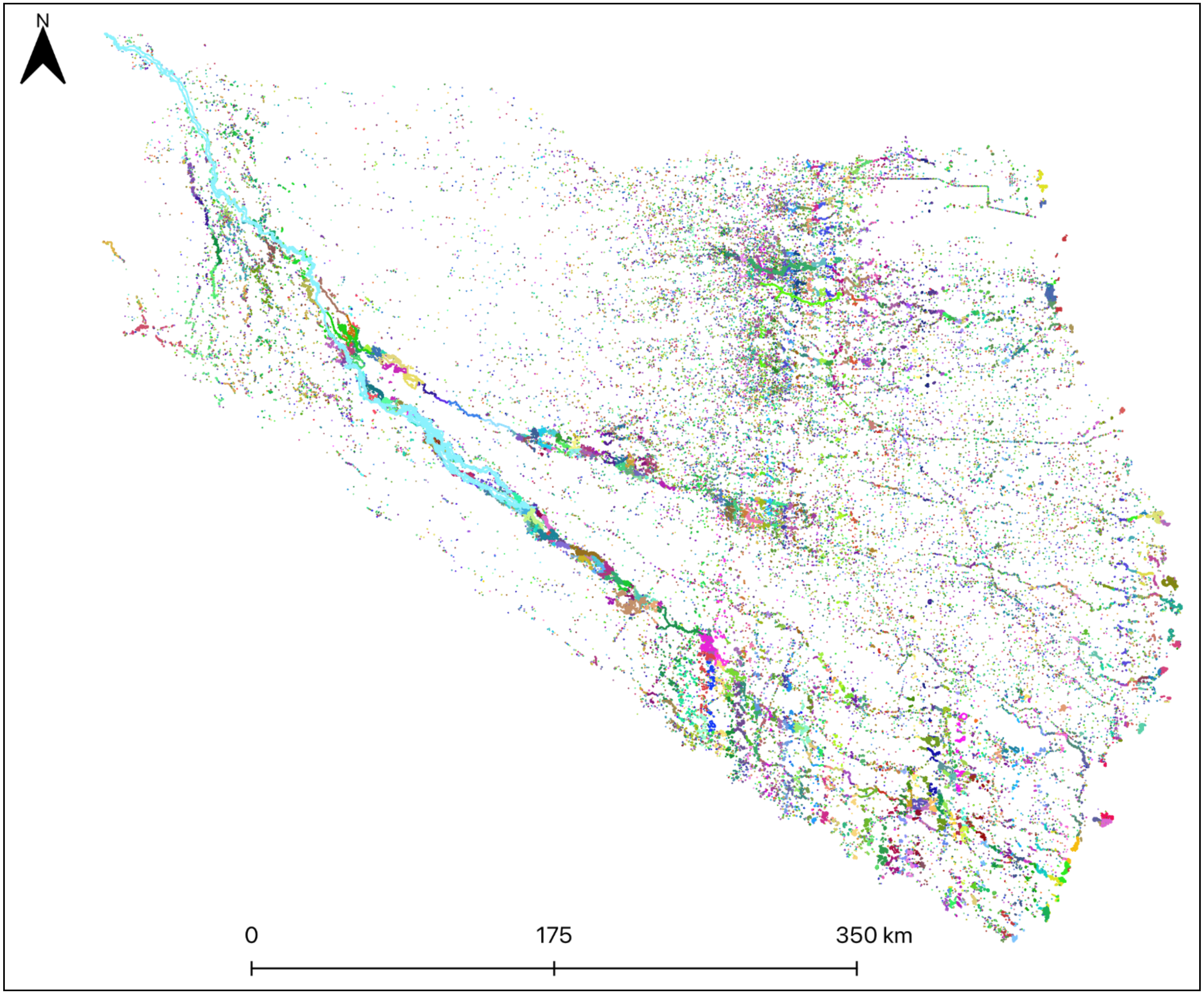

Figure 5.1A. Results from the segmentation procedure in which 85,930 objects were formed. The colors are randomly assigned based on the object ID number.

	Class name	Threshold value
SIZE CLASSES	Large	*Object surface area* >= 6595.4 m^2
	Medium	6595.4 m2 > *object surface area* > 765.7 m^2
	Small	*Object surface area* <= 765.7 m^2
SATURATION CLASSES	High extent - High frequency	*Object mean extent* >= 0.76 *Object mean* frequency >= 0.14
	High extent - Low frequency	*Object mean extent* >= 0.76 *Object mean* frequency < 0.14
	Low extent - High frequency	*Object mean extent* < 0.76 *Object mean* frequency >= 0.14
	Low extent - Low frequency	*Object mean extent* < 0.76 *Object mean* frequency < 0.14

Table 5.1. The threshold values of surface area (in m^2), mean extent, and mean frequency that define each object's final surface water class.

More specific patterns emerge upon examining the objects by their surface water class using a variety of visualization methods. Starting simply, the thresholds of surface area (in m2) used to define the size and the mean values used to define the extent and frequency classes are displayed in Table 5.1. The left side of figure 5.1B then offers the numeric distribution of objects' extent and frequency values by size class. The right side of the figure provides an overview of the numerical distribution of the extent and frequency index values relative to size in order to illustrate the pattern of the *large* size class tending to have higher frequency index values yet lower extent index values while the *small* size class tending to display the opposite pattern.

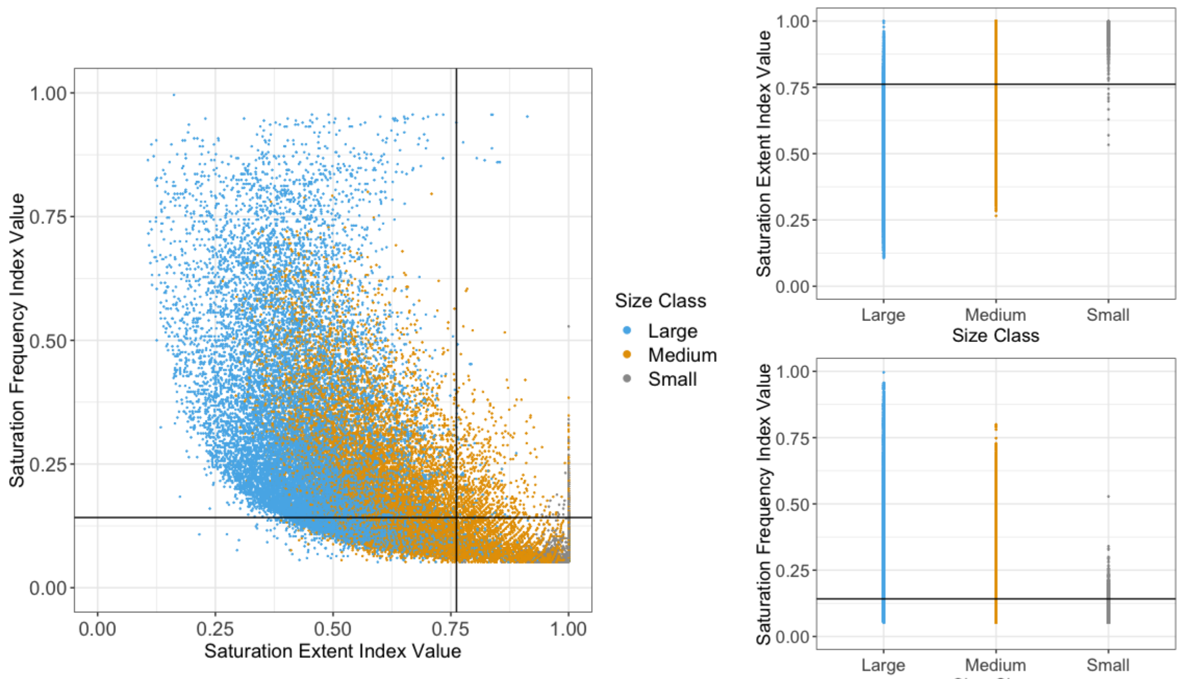

Figure 5.1.B. (Left) The distribution of surface water sources according to their saturation and size classes. The solid black lines demarcate the sample mean of the extent (vertical line) and of the frequency (horizontal line). Because the minimum number of valid observations was set to 13 in the segmentation, there are no sources with a frequency of less than 0.05. (Top right) Size class v. saturation extent index values and (bottom right) saturation frequency values plots that illustrate the correlation between the large and small size classes relative to extent and frequency values, with the solid black lines indicating the mean values for each. Large sources tend to have frequency values above the mean frequency but extent values below the mean extent, while small sources demonstrate the opposite trend.

5.2. Surface water class availability and distribution

From this point forward, I refer to the *objects* representing surface water solely as *surface water sources*, *sources of surface water,* or, simply, *sources*. Semantically, the term *sources* better reflects the "real world" implications of the classification with the exception of references to the processes in which the objects representing surface water were originally formed. When referring to the specific "types" of water sources according to my classification, I will continue to use the term *surface water classes*. Figure 5.2A through figure 5.2.C depict the density of the different classes across the landscape, while figure 5.2.D shows the real-world examples of the types of surface water sources that are found in each class. Figure 5.2E illustrates the classes most likely to be encountered based on a sample of 75,000 random points throughout the basin, and figure 5.2F shows the distribution of the classes throughout the basin.

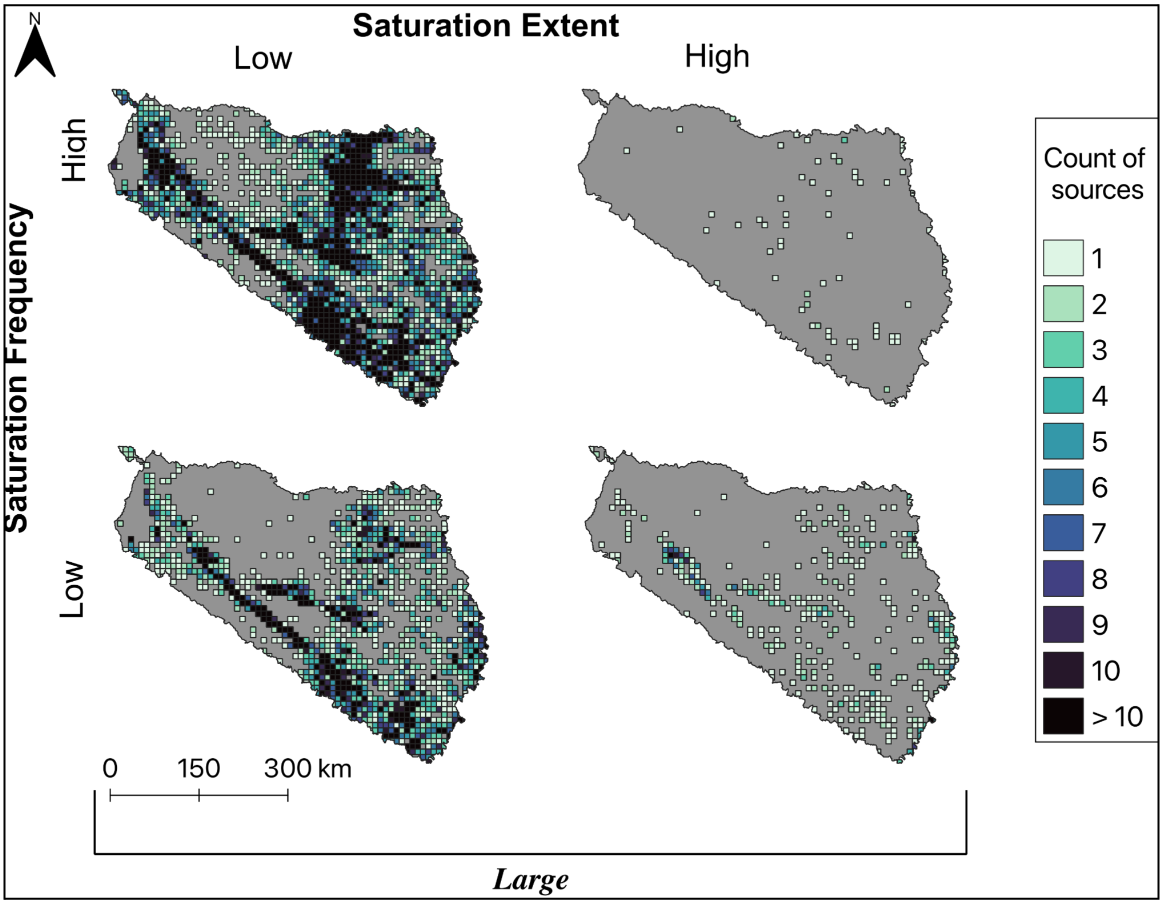

Figure 5.2A. Density of the large sources of different saturation classes throughout the basin. Each surface water source was binned into a 10x10 km grid to legibly depict the broader patterns of surface water distribution.

The *large* size class includes the Pilcomayo River as well as sources that appear to be wetlands, intermittent streams, oxbow lakes, and several large, naturally-occurring pools of water, as shown in figure 5.2B, which displays examples of the real sources of surface water that are represented within each class. As figure 5.1B demonstrated, the *large* size class is well-represented in the *high frequency* quadrant. In fact, the *large* size class has the highest between and within-class proportion of sources in the *low extent - high frequency* class, with 16.39% of all the sources represented, compared to 10.09% in the *medium* size class and 0.01% in the *small,* and approximately 66% of all the *large* sources falling within this class. Figure 5.2A outlines the density of the *large* saturation classes across the basin and show that the *large - low* *extent - high frequency* class, occur in the highest concentrations along the Pilcomayo River; in the southeast of the basin; and in a considerable portion of the Central Chaco, with particularly high densities around the Mennonite colonies. This is also the class most likely to be encountered in these regions according to Figure 5.2E. Nevertheless, the *large* class is the least represented within both the *high extent - high frequency* and the *high extent -low frequency* classes, with less than 1% of the *large* sources represented in each.

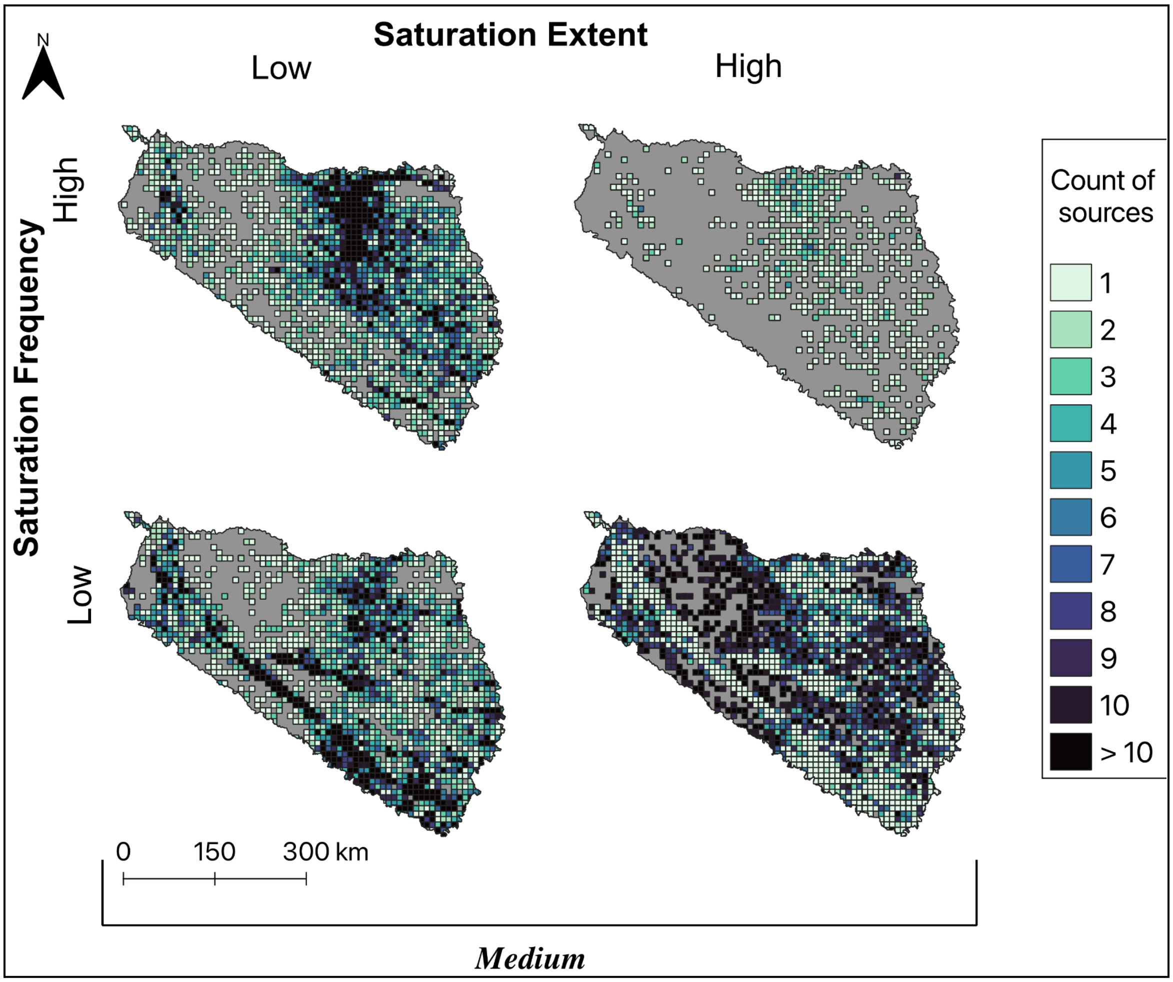

Figure 5.2B. Density of the medium sources of different saturation classes throughout the basin. Each surface water source was binned into a 10x10 km grid to legibly depict the broader patterns of surface water distribution.

The *medium* size class includes reservoirs, depressions in the landscape that fill intermittently with flooding or heavy rainfall, and disjointed portions of the Pilcomayo River itself and its associated wetlands as well as intermittent streams in other parts of the landscape, as can be seen class since it contains 50% of all sources of surface water, and this also affords it a broader spread across the saturation classes as well. It is densely concentrated in the northwest, north-central, and central-east regions of the basin. In fact, the *medium - high extent - low frequency* class is among the few classes represented in the northwest of the basin, where sources are sparsely distributed overall.

From figure 5.2F, it appears that for the *medium* size class, the *high extent - low frequency* class is also prevalent along the banks of the Pilcomayo River; however, upon viewing figure 5.2B, it is the *low extent - low frequency* class that is the most densely concentrated around the river, especially along its lower branch, and its associated wetlands. There is also a dense concentration of the *medium - low extent - high frequency* class in the Central Chaco, overlapping with the area that the *large - low extent - high frequency* also populates densely. Finally, the *high extent - high frequency* class, though less widely and densely distributed across the landscape overall in comparison to the other saturation classes, is well-represented for the *medium* size class, though mainly in the north-Central Chaco and sparsely dispersed in the east.

The *small* class contains the same types of sources that the *medium* possesses; however, it hosts a higher proportion of sources occurring within the *high extent - low frequency* class, with about 98% of its sources falling within it. The densest regions of the *small - high extent - low frequency* class occur along the borders of the Pilcomayo River and its associated wetlands, in the southeast, and in the Central Chaco. They also track closely with those of the *large - low extent - high frequency class* and are abundant in the Central Chaco, dispersed areas around the eastern edge of the basin, and south of the Pilcomayo River. In contrast to the wider distribution of the *medium* class, the surface water sources of the *small* class are rarely found in the northernmost portion of the basin in both the Dry and Humid Chaco, as seen in figure 5.2C and figure 5.2F. This may be due to errors in the Landsat satellite imagery that were then reproduced in the GSWD dataset for smaller areas of water.

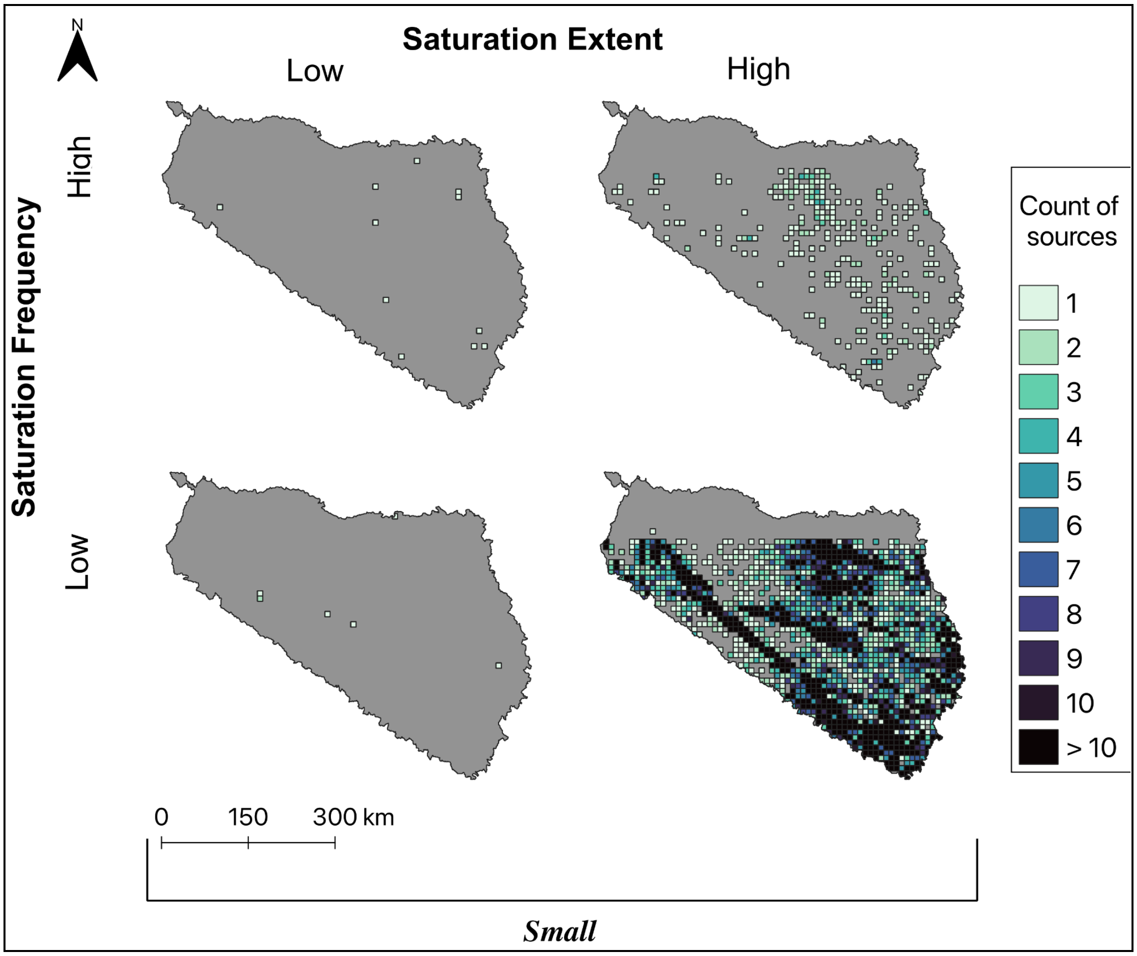

Figure 5.2C. Density of the small sources of different saturation classes throughout the basin. Each surface water source was binned into a 10x10 km grid to legibly depict the broader patterns of surface water distribution.

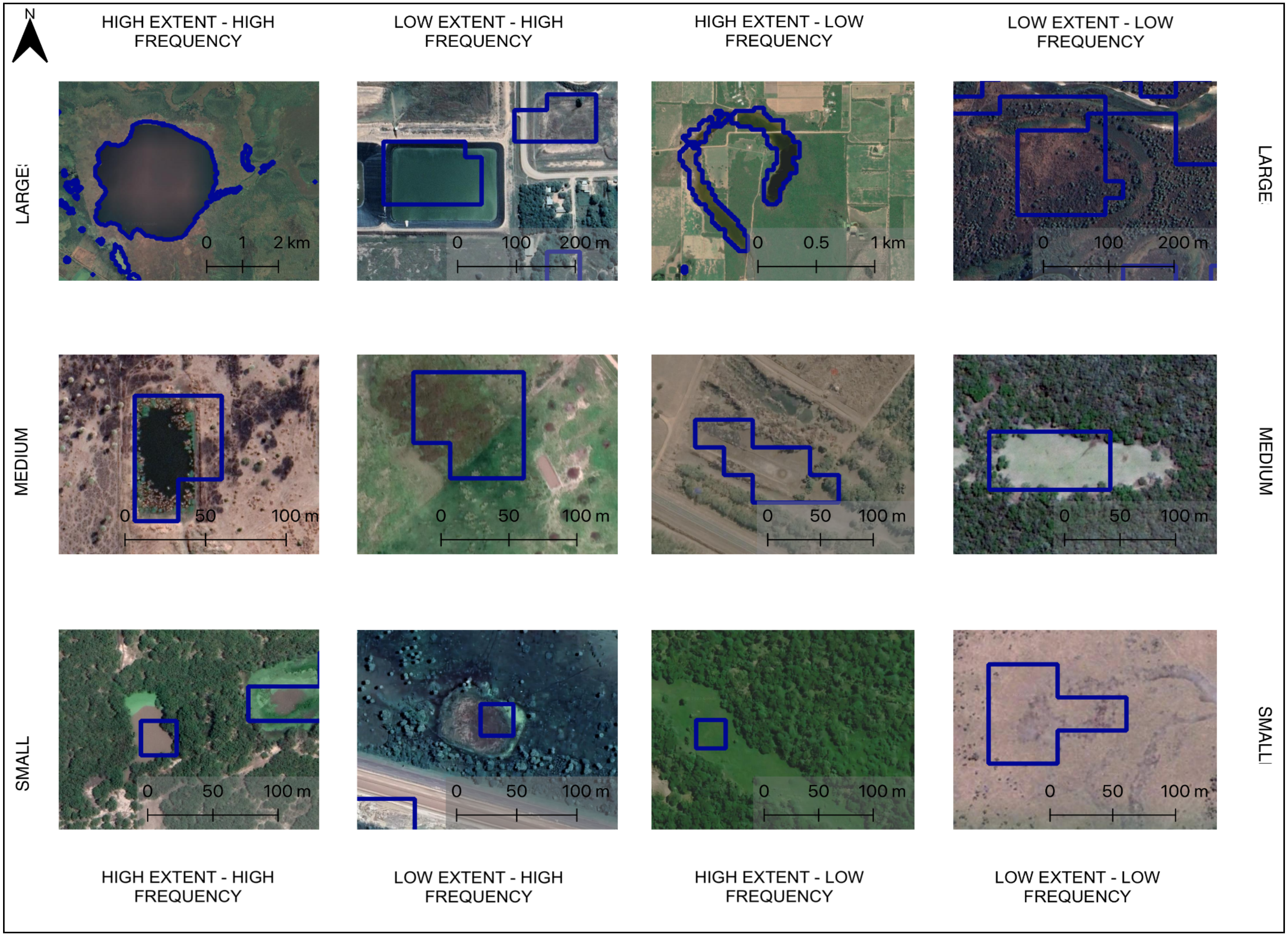

Figure 5.2D.Examples of the types of surface water sources belonging to each of the 12 surface water classes.

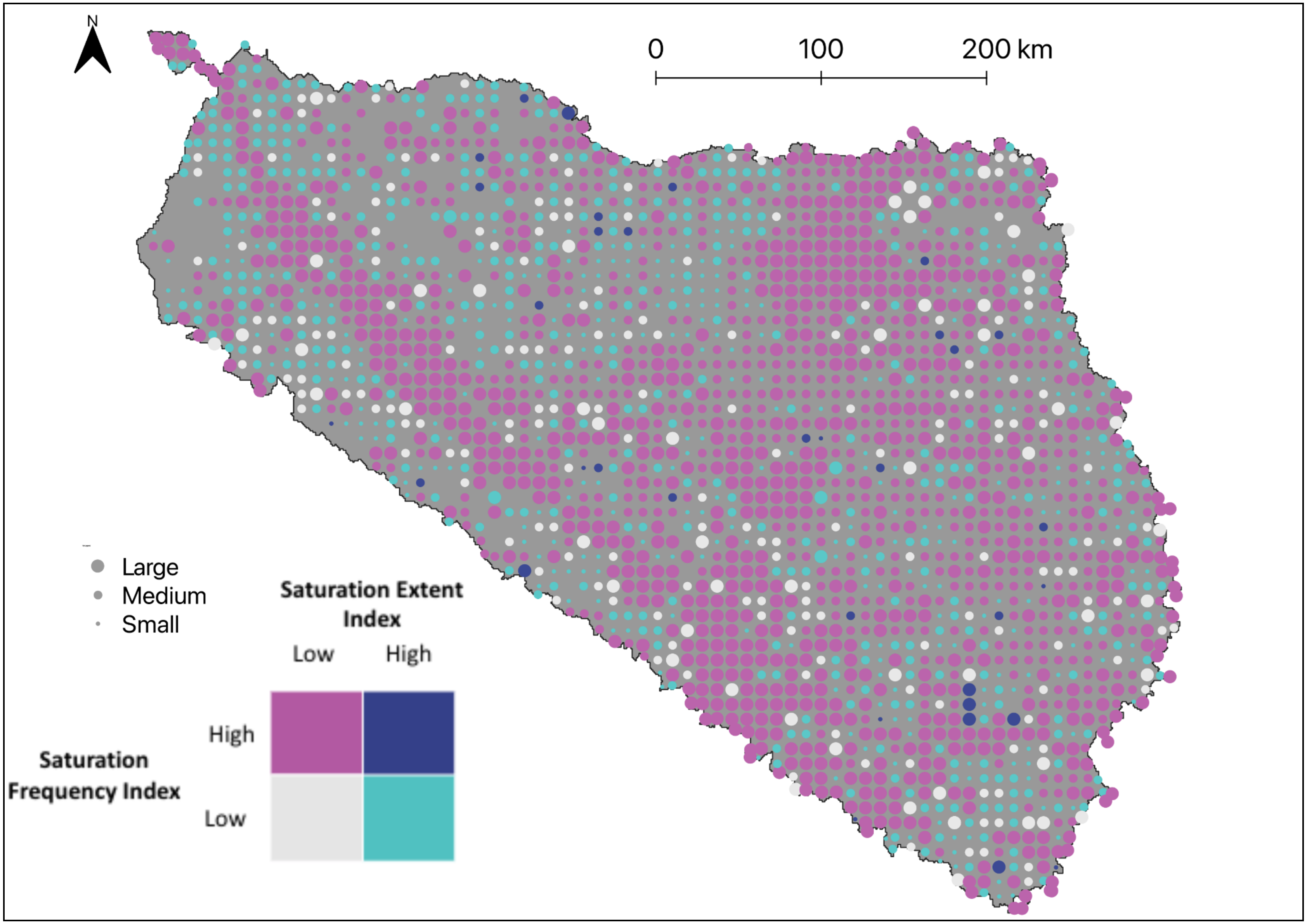

Figure 5.2E. The surface water class most likely to be encountered across the basin based on a random sample of 75,000 points dispersed throughout the basin.

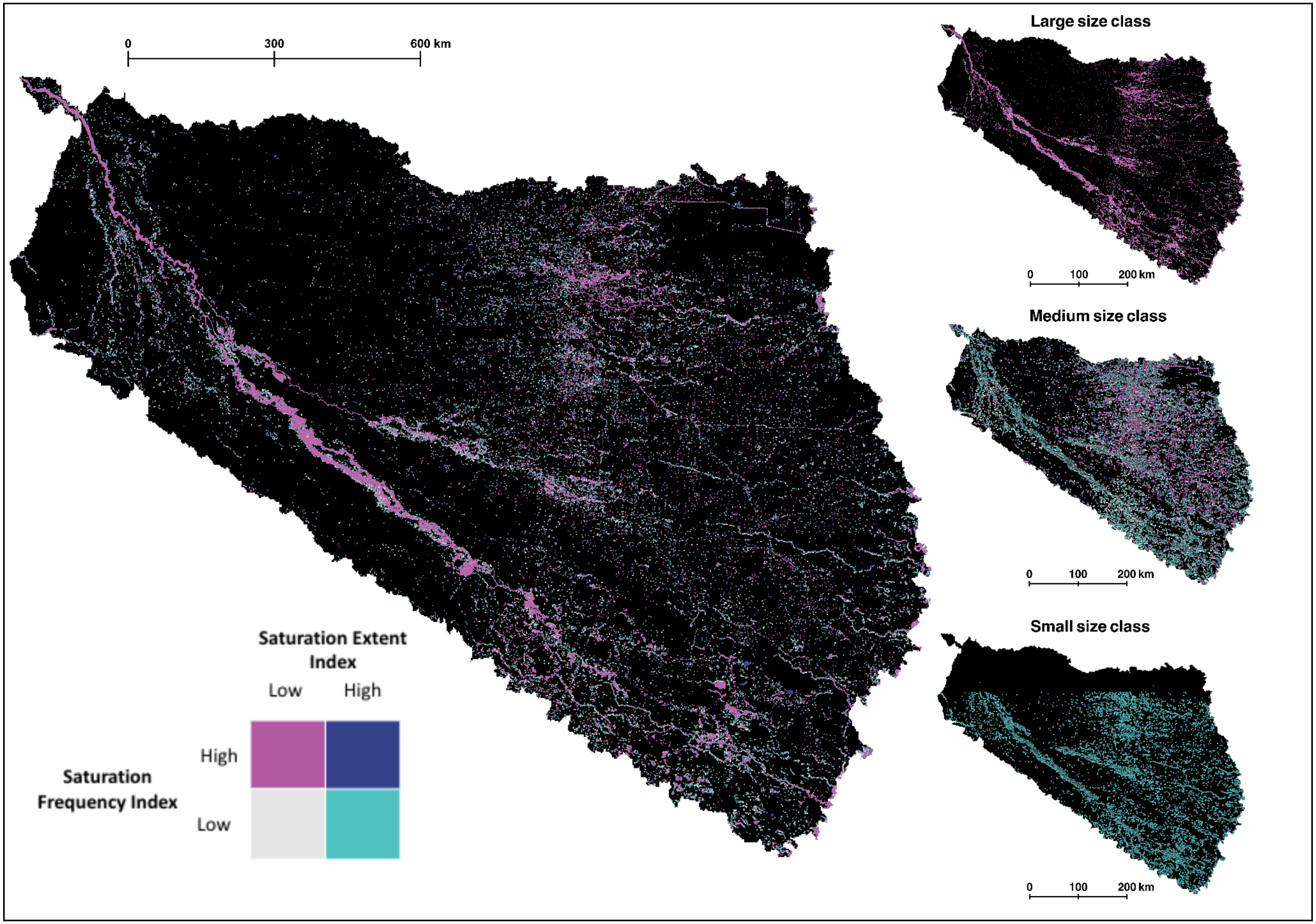

Figure 5.2F. The 12 surface water classes represented throughout the region.

5.3. Settlements that lost and gained access to surface water classes

In the year 2000 (baseline), over 81.00% of the settlements in each of the four types had access to at least six of the 12 surface water classes. For 19.02% of all settlements, at least half of the classes originally accessible to them transitioned to being completely inaccessible by 2020, meaning that they fell beyond the 15 km threshold. In fact, 16.99% of all settlements lost access completely to all classes and, by extension, to all surface water sources. Figure 5.3 illustrates the proportion of classes that were lost between 2000 and 2020 per settlement across all four settlement types. The *emerging* settlements saw the highest proportion of complete loss of access among the four settlement types, with 48.33% having no accessible surface water by 2020. However, I suspect that the access loss was overestimated for this particular type due to discrepancies in the land cover/use data and high clustering of the *emerging* settlements with the areas where these discrepancies were greatest. I explain these issues in detail in chapter 6. Additionally, the *emerging* settlement type possessed the fewest number of settlements (n = 60), half of which are spatially clustered together in the region where the discrepancies occur, in contrast to the wider spatial distribution of the other types. Their close spatial clustering translated to land cover/use changes in the region of clustering having a larger impact on aggregated data for the *emerging* type. Nevertheless, the other settlement types also held considerable proportions of settlements that experienced complete loss of access to surface water by 2020. The *disappearing* settlements had the second highest proportion of loss at 36.09%, while 19.61% of *Indigenous* settlements experienced complete loss. The *persisting* settlements had the lowest proportion of settlements that experienced complete loss (10.66%).

Each settlement type also possessed settlements with no surface water source of any class within 15 km at baseline, leaving these settlements with no reasonably accessible surface water according to my parameters. In total, there were 68 settlements (6.56%) across all settlement types with no access to surface water at any point during the time period. Within the settlement types, the *Indigenous* held the highest proportion of settlements with no access (10.78%, n = 11), while the *emerging* had the lowest proportion (1.67%, n = 1). These are represented in figure 5.3 as black symbols corresponding to the settlement type.

A small proportion of settlements across all four types gained access to either one or two additional classes (5.79% and 0.39%, respectively), as shown in figure 5.3. The *persisting* type had the highest proportion of settlements that gained access to new classes (6.88%), though the *Indigenous* type came at a close second with 6.86%. The *disappearing* and *emerging* had the lowest proportion of settlements with gains, standing at 3.01% and 3.33%, respectively. However, gains in access to surface water *classes* did not necessarily signify that access to surface water *overall* was increasing. Rather, the gain in access to *classes* could still occur simultaneously with an increase in the distance to surface water (i.e., reduced access), as I will explain in the proceeding sections.

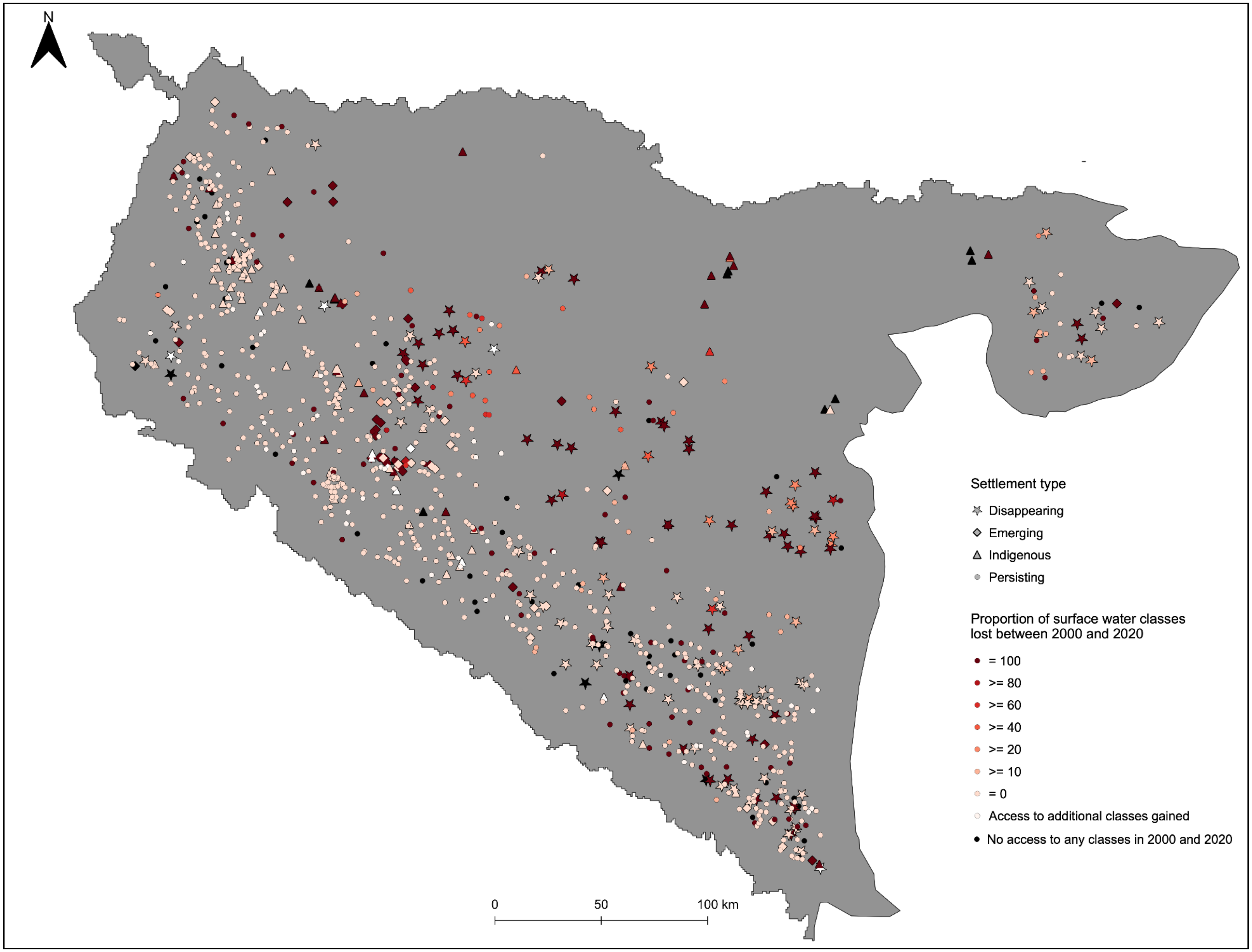

Figure 5.3. The proportion of surface water classes lost between 2000 and 2020 for each settlement.

5.4. Broad patterns in transitions in the most accessible surface water class

All four settlement types share certain trends in their overall access to different classes. Figure 5.4 shows the proportion of each settlement type for which the *most* accessible (i.e., the closest in distance) source of surface water changed to a source of a different class from 2000 to 2020. In both years, the *large - low extent - high frequency* class was the closest class to the highest proportion of settlements of all four types (the *low extent - high frequency* saturation class includes surface water sources that frequently hold water in some parts though not all of their spatial extent). The class is the most spatially ubiquitous across most of the basin's extent, as displayed in figure 5.2A and figure 5.2E. In addition, for the *disappearing*, *persisting*, and *Indigenous* types, the proportion of settlements with the *medium - low extent - high frequency* class increased, while for the *emerging* settlements, the proportion decreased.

The *high extent - high frequency* saturation class was among the least universally accessible, with all of its size iterations being the closest source to less than 5% of the settlements within each type. This is of particular concern since this saturation class possesses the sources that most frequently hold a relatively high proportion of water (i.e., the most spatially-temporally stable sources). This quality makes them the most "useful" surface water sources to settlements since they are the most likely to hold more water than the sources of other classes throughout the year. By 2020, sources of the *large - high extent - high frequency* were no longer the closest to any *disappearing* settlement and the *Indigenous* settlements lost all three *high extent - high frequency* size classes as their closest sources by 2020. The *emerging* settlements had no settlements with the closest access to these classes in either year. The *persisting* is the only type with settlements that had the closest access to all three of the size classes of the *high extent - high frequency* in 2000 and 2020.

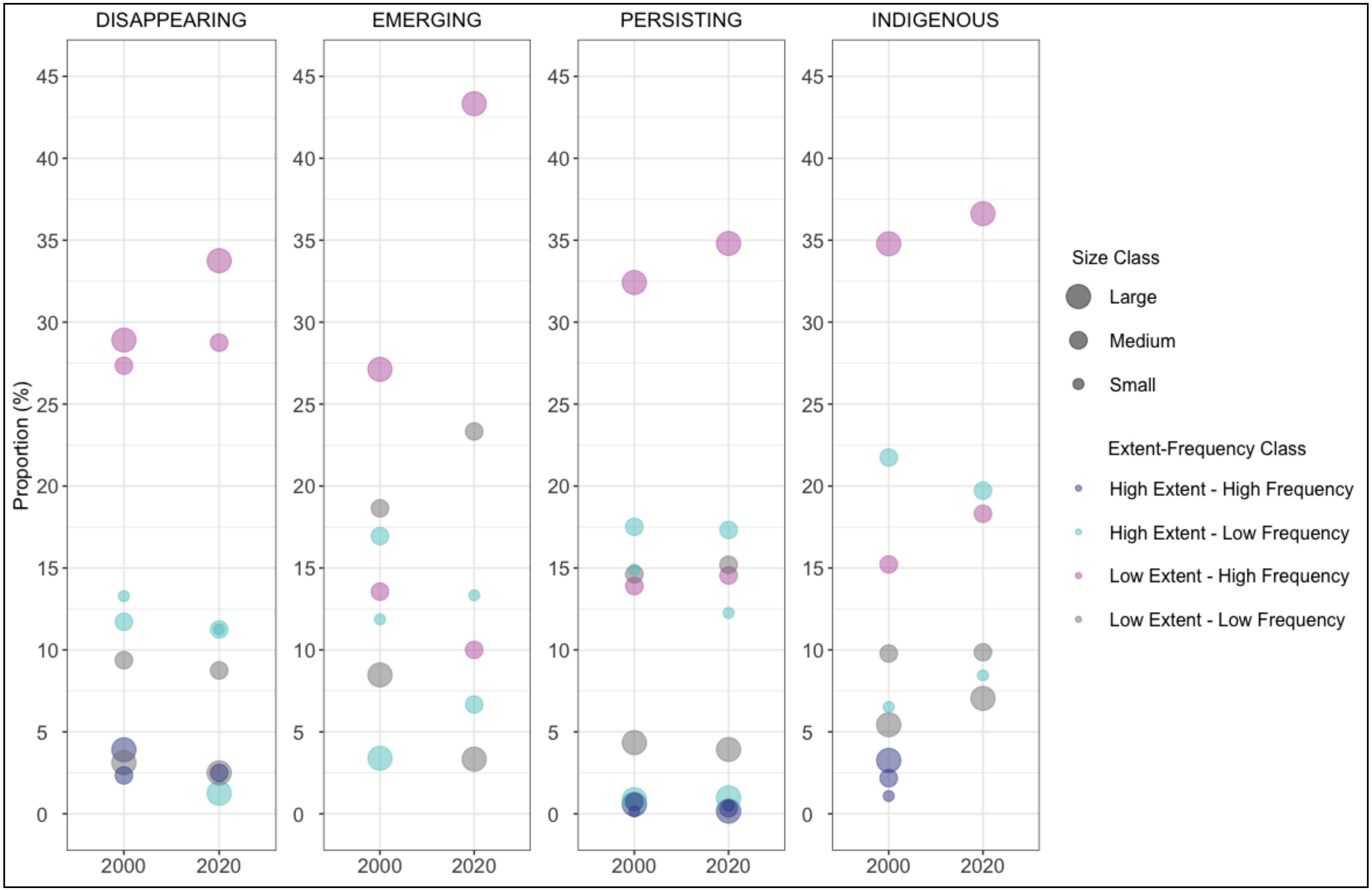

Figure 5.4. The proportion of settlements for each settlement type whose closest surface water source was of a given surface water class.

5.5. Settlement-level transitions in the most accessible surface water classes

The single most accessible source of surface water (i.e., the closest one in km) transitioned to a source of a different class by the year 2020 for 27.12% of all settlements, while 66.70% of all settlements did not experience any transitions in the most accessible class in 2000 and 2020. The remaining settlements had no access to surface water within 15 km in either 2000 or 2020. Settlements that had access to surface water in the year 2000 and lost access by 2020 are included in the transitioning settlements. Figure 5.5A displays the transitions for the settlements that experienced a transition, including the settlements that had access to surface water in 2000 but had lost access to by 2020. Figure 5.5B provides a visualization of the classes that the non-transitioning settlements maintained access to.

Overall, among the settlements that transitioned, the changes in both type of and distance to the closest source tended to be unfavorable for livelihood viability. First, the settlements that transitioned and retained access to surface water in 2020 saw a mean increase in distance of 0.77 km and a median increase of 0.08 km to the closest surface water. The *disappearing* settlements have the highest averages (mean = 1.72 km, median = 0.93 km), a result that is consistent with those outlined in section 5.3, as these settlements tended to experience more challenges in accessing surface water than their counterparts.

Second, although in 2000, there were 19 settlements with the *high extent - high frequency* saturation class as their closest source, by 2020, there were only three, none of which were the original settlements. In fact, 11 of these original settlements lost all access to surface water in 2020, and 2 transitioned to the *medium - low extent - low frequency* class, the least "useful" of the three saturation classes (regardless of the associated size) due to its low spatial-temporal stability. Overall, 72.24% of the 281 settlements that experienced transitions either had closest access to the least useful classes, or were without access to surface water altogether.

Among the settlements that did not transition, the average distance to the closest source decreased by 0.15 km by 2020, indicating that access to these sources slightly increased over time. The median change in distance also revealed a decreasing trend, though at less than half of the mean (0.06 km). Considering these represent relatively small magnitudes of decrease, slightly shorter pathways to surface water sources of this class likely opened as areas of cropland and pasture withdrew somewhat. Small changes in land cover can have a considerable impact on the opening or closing of corridors of access, a finding that I elaborate on further in section 5.7. In addition, the *large - low extent - high frequency* class was most commonly the closest to these settlements. Considering sources of the *large* size class cover more surface area, slight shifts in land cover around these sources could cause some portions of them to become more accessible to nearby settlements.

The *persisting* and *Indigenous* held the highest proportions of settlements with no change in the most accessible water body class (73.41% and 62.75%, respectively). This is consistent with these two settlements also experiencing the lowest proportion of class loss relative to the *disappearing* and *emerging* settlements (as discussed in section 5.3). Less than half of the settlements in the *disappearing* and *emerging* settlement types were non-transitioning (47.37% and 33.33%, respectively), which suggests that these types endured greater land use change. Once again, however, the magnitude of loss in classes for the *emerging* type is questionable since these settlements were spatially clustered in a region in which the land cover/use dataset likely misidentified many of the pixels as cropland and pasture.

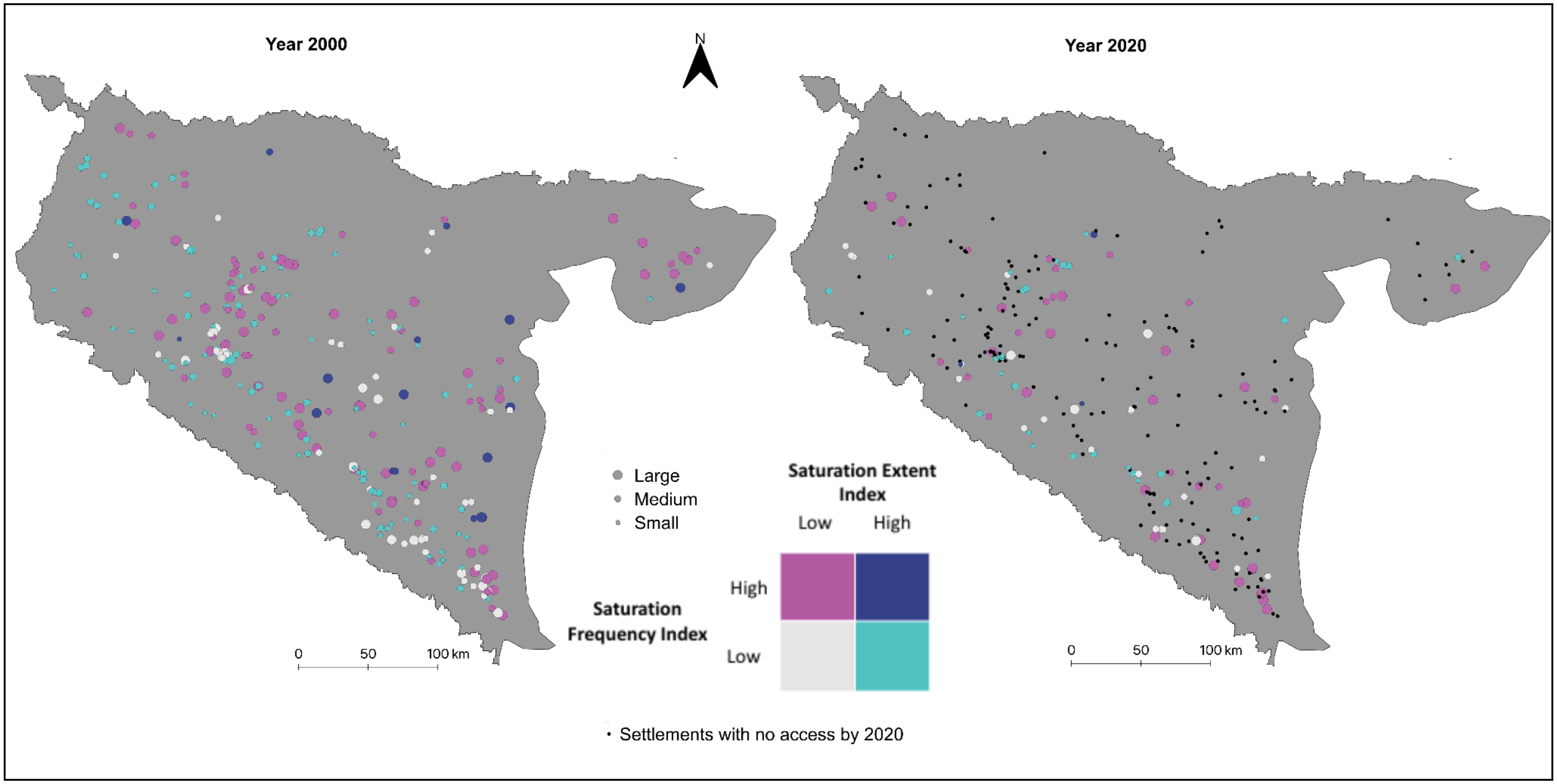

Figure 5.5A. Individual transitioning settlements represented as the class of the source closest to them in the years 2000 and 2020. The four different settlement types are not differentiated here. The black dots represent settlements that completely lost access to all surface water by 2020.

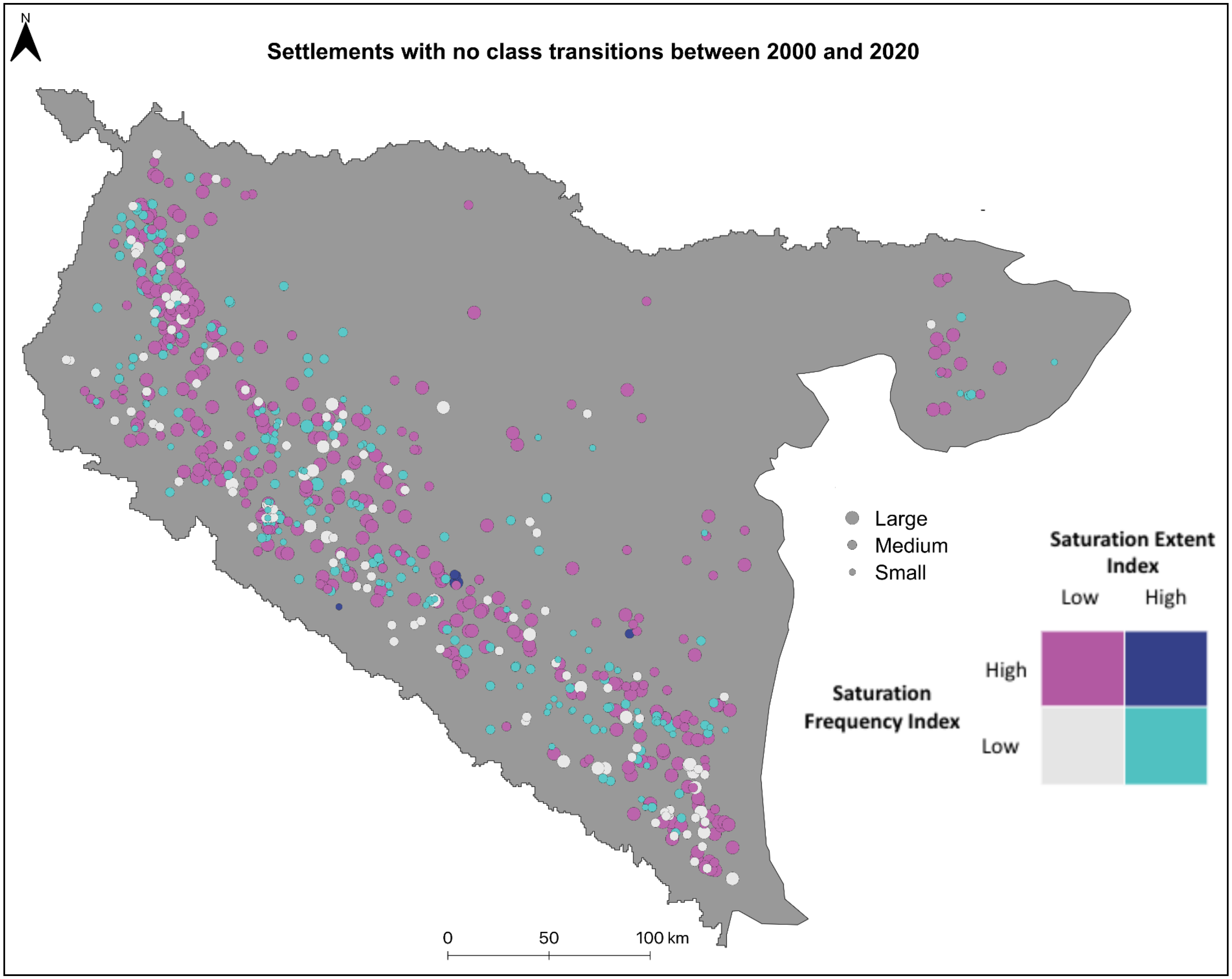

Figure 5.5B. Individual non-transitioning settlements represented as the class of the source closest to them in the years 2000 and 2020. The four different settlement types are not differentiated here.

5.6. Universal decreases in access at different rates across settlements and classes

Across all settlement types and saturation classes, annual median distance to surface water universally increased between 2000 and 2020, as Figure 5.6 displays. Surface water sources of the *low extent - high frequency* saturation class (surface water sources that frequently hold water in some parts though not all of their spatial extent) was the most consistently accessible saturation class among the *disappearing, persisting*, and *Indigenous* settlements both annually and overall. This finding is consistent with the results shown in figure 5.4, which showed that sources of the *large low extent - high frequency* surface water class were the closest to the highest proportion of settlements for these three types. The *disappearing*, *persisting*, and *Indigenous* settlements had both the shortest absolute annual median distance and the lowest overall increase in median distance between 2000 and 2020 to this class compared to the *high extent - high frequency* and *high extent - low frequency* classes. Nevertheless, among these three settlement types, the *disappearing* experienced the highest increase in overall median distance at 1.24 km, which is 0.98 km higher than the *persisting* and 1.16 km higher than the *Indigenous* settlements' overall increases. In addition, while the *persisting* and *Indigenous* settlements saw only gradual increases in median distance over time to this class, the *disappearing* settlements experienced periods of higher-magnitude increases between 2012 and 2013 and between 2014 and 2020. The same pattern holds for the three other saturation classes as well for the *disappearing* settlements. This finding suggests the expansion of cropland and pasture impacted *disappearing* settlements slightly more than the other settlements.

In contrast to their counterparts, the annual median distance values indicate that the *emerging* settlements had slightly more consistent access to the *high extent - low frequency* class than to the three other saturation classes. This class represents surface water sources that hold water in a relatively high proportion of their spatial extent, but with a lower frequency of occurrence. *Emerging* settlements also experienced the lowest overall increase in distance to this class (0.70 km) than to any of the other saturation classes, further indicating that sources within this class remained among the most accessible to the *emerging* settlements overall. Moreover, sources of the *high extent - low frequency* class were the closest in distance to 32.30% of *emerging* settlements in 2000 and 20.00% in 2020. However, as observations from figure 5.4 show, a higher proportion of *emerging* settlements were closest to sources of the *large - low extent - high* *frequency* class in both years (40.68% and 53.33%, respectively). This is likely due to two factors: (1) the more extensive spatial distribution of this class, and (2) the close clustering of *emerging* settlements along the Pilcomayo river (which was classified as *large - low extent - high frequency*).

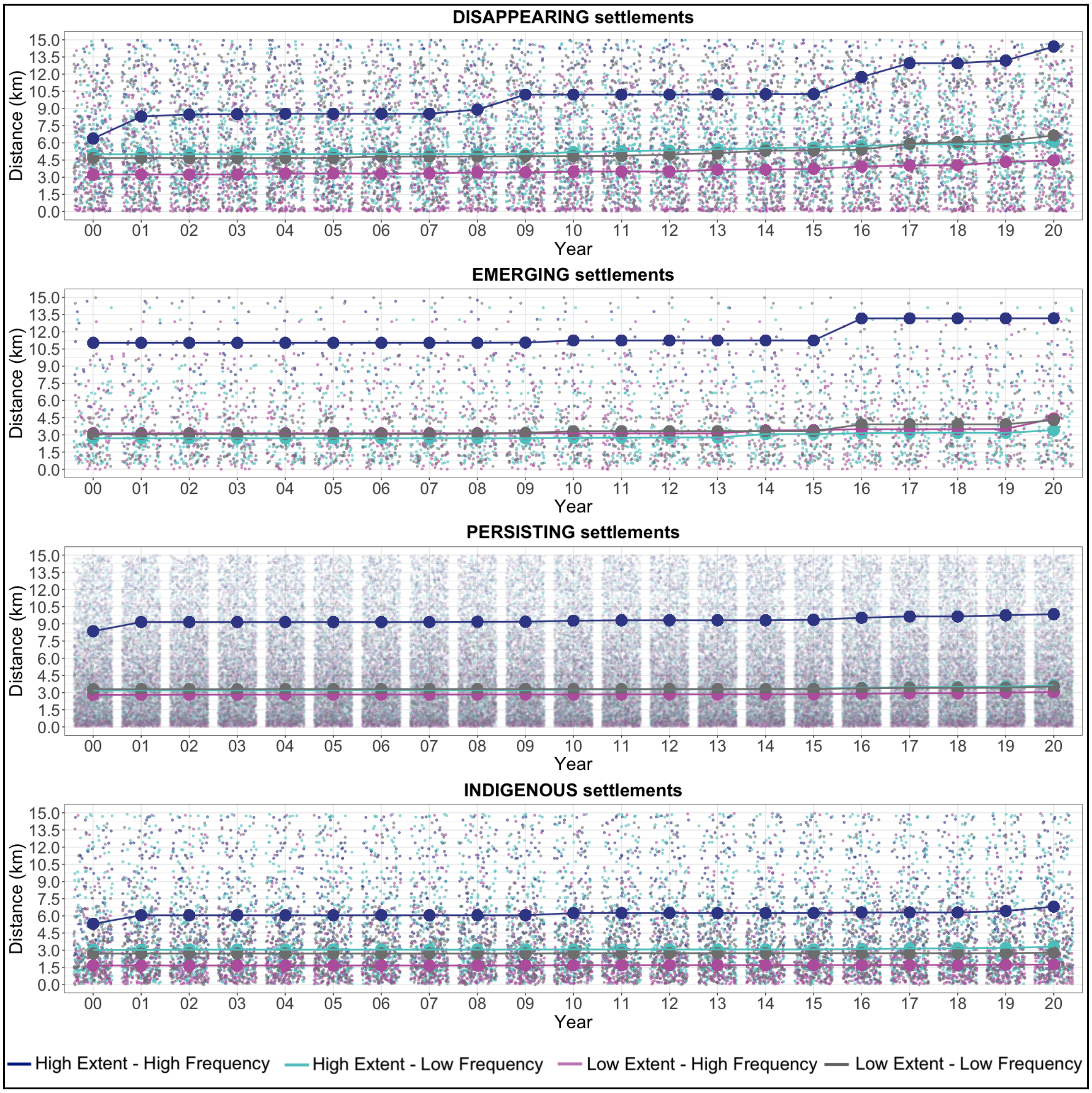

Figure 5.6. The distance values from all settlements of the four settlement types to all surface water sources (represented as the small jittered points) of each of the four saturation classes within a 15 km radius of the settlements in the year 2000. The large points and connecting lines represent the median annual distance for each saturation class. For readability, the sources that were at distances > 15 km are not shown in the figure, but they still factor into the annual median distances.

5.7. Diminished access to the most "useful" saturation class across all settlements

As the results in sections 5.4 and 5.5 demonstrated, the *high extent - high frequency* saturation class, composed of the most useful surface water sources, often became the most difficult class to access over time. Figure 5.6 thus offers further insight into the annual and interannual changes in access to this class from the fixed settlements. Sources of the *high extent - high frequency* class were the furthest median distance from all settlements in every year from start to end and also experienced the highest overall increases in median distance between 2000 and 2020 within each settlement compared to the other three saturation classes. This demonstrates that, universally, settlements had the least access to the most useful class throughout the full 21-year period, and as expected, access was even lower in 2020 than in 2000.

Between the settlement types, the *Indigenous* settlements had the lowest absolute annual median distances to sources of the *high extent - high frequency* class, and the second lowest change increase in overall median distance at 1.50 km. The *persisting* settlements' overall change was only 0.02 km lower. These findings indicate that the *Indigenous* settlements had slightly better access to the most useful surface water sources than their counterparts, but their access to these sources has still been increasing over time, as they remain vulnerable to the effects of the expanding agricultural frontier. Although much of the trajectory showed a relatively gradual increase in distance, there were two periods of notable upticks in distance values: one between 2000 and 2001 and the other between 2019 and 2020.

The *disappearing* settlements, on the other hand, followed a more volatile trajectory with four distinct interannual upticks in distance (two of which correspond to those cited for the *Indigenous* settlements as well), and the highest overall increase in distance to sources of this class. The *disappearing* settlements started with a lower median distance to sources of the *high extent - high frequency* class than the *emerging* and *persisting*. However, the upticks of between 2000 to 2001, 2007 to 2009, 2015 to 2017, and 2019 to 2020 set the *disappearing* type's 2020 median distance to 14.41 km. This represents an 8.03 km increase in overall median distance between 2000 and 2020, 5.89 km higher than that of the *emerging* settlements, which experienced the second highest overall increase at 2.14 km. Consequently, the *disappearing* settlement type experienced the highest rate of access loss, suggesting that these settlements had higher exposure to agricultural land use changes. The *disappearing* settlements' higher rates of loss to the most useful class, as well as to the other classes, highlight these settlements' greater vulnerability to losing access to surface water altogether, as seen in figure 5.3.

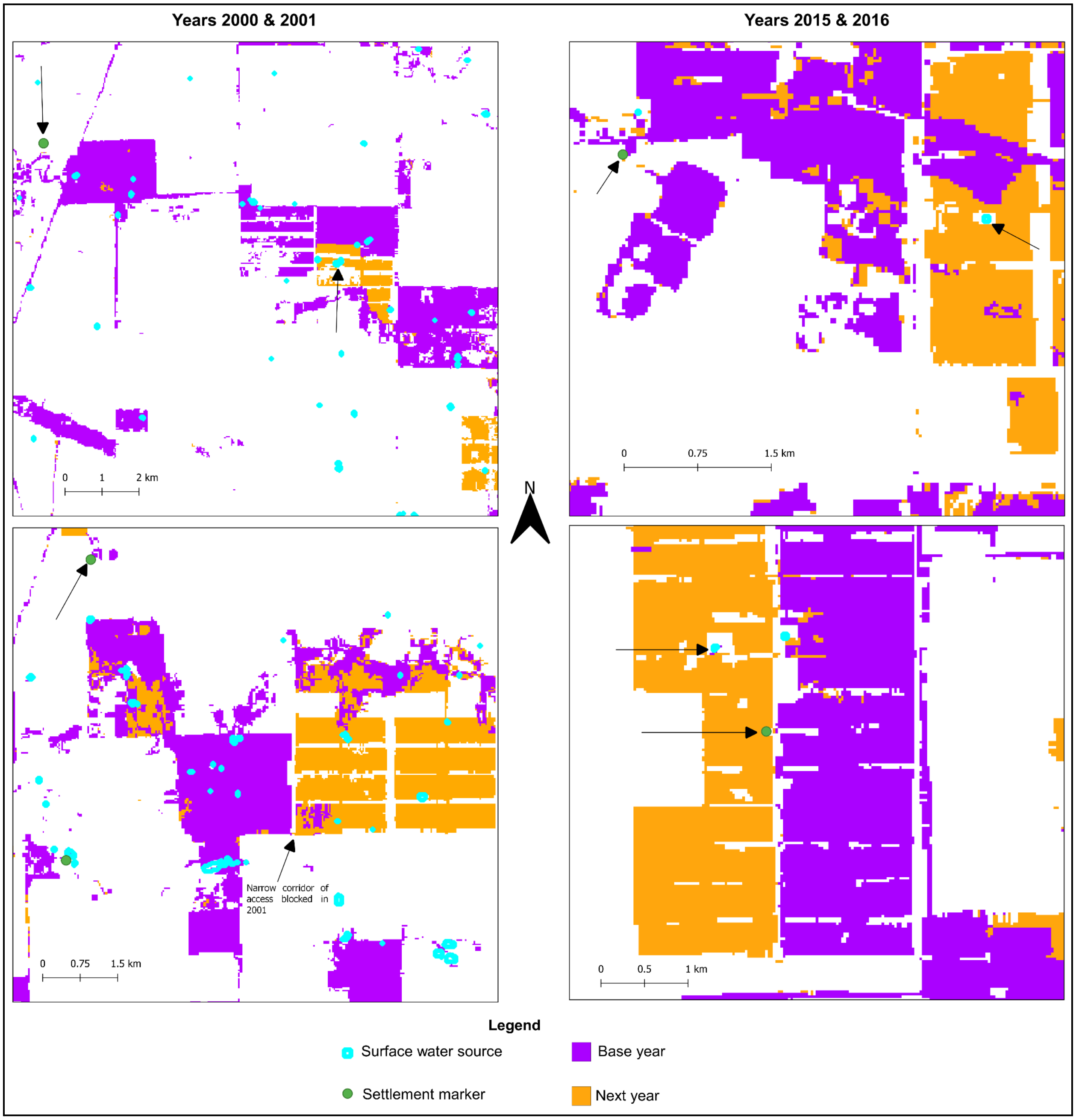

Figure 5.7. Examples of changes in land cover classified as cropland/pasture between 2000 and 2001 (left) and 2015 and 2016 (right) that resulted in increased distances for the indicated settlements to the indicated source of surface water. The purple shows the area that existed as cropland/pasture in the base while the orange represents the increased area of conversion in the next year.

As pointed out in the specific discussion of the *Indigenous* and *disappearing* settlements, there were also specific interannual patterns that emerged concerning access to sources of the *high extent - high frequency* saturation class. The aforementioned settlements along with the *persisting* all experienced an increase in median distance of at least 0.75 km in distance to surface water sources in this class between the years 2000 and 2001. The *emerging* settlements, in contrast, only saw one notable uptick in the 21-year period between 2015 and 2016 (1.92 km increase between the two years), with the *disappearing* also experiencing an uptick here of 1.49 km. The *persisting* and *Indigenous* settlements only saw slight increases during this period (0.17 and 0.06 km, respectively). The last primary period of high increases in median distance was at the very end of the 21-year period and was most impactful for the *disappearing* settlements (1.22 km increase) and slightly impactful for the *Indigenous* (0.39 km). The *emerging* and *persisting* were least affected during this period, experiencing increases of 0.01 and 0.10 km, respectively. Figure 5.7 shows four specific examples in which agricultural landholdings reduced settlements' access to a surface water source between the years 2000 and 2001 and 2015 and 2016. This figure illustrates how small, localized changes such as the blocking of narrow corridors of access (seen in the bottom left) and the direct enclosure of settlements themselves (seen in the two examples on the right) can make considerable differences in the accessibility of surface water.

5.8. Direct enclosure of settlements

187 settlements were eventually enclosed by agricultural landholdings at some point between 2001 and 2020 (18.05% of the total sample). These settlements were dropped from the cost-distance algorithm in the year of their enclosure. Figure 5.8A shows the annual proportion of settlements in each settlement type with a source of each saturation class within 15 km. Figure 5.8B shows the statistical distribution of the difference in distance in the year 2000 and the last year of consideration for the settlements that remained during all 21-years (making their last year 2020), those that were dropped, and for both of these combined.

By settlement type, the *emerging* had the highest overall proportion of settlements that dropped from the sample, with 50.00% becoming enclosed by 2020. It also experienced several periods of steep declines in the proportion of settlements without access to the saturation classes. However, as mentioned in section 5.3, half of the *emerging* settlements were clustered in an area in which the land cover/use data could not accurately distinguish land cover types. These were among the settlements that dropped out of the sample over time, though *emerging* settlements in other regions outside the cluster also dropped out of the sample for some classes. As a result, the proportional loss of *emerging* settlements was likely overestimated.

The *disappearing* settlements had the second highest proportion of settlements dropped at 39.10%, while the *Indigenous* and *persisting* settlements stood at 20.59% and 11.34%, respectively. Across all the settlements collectively, the *disappearing* are the most disproportionately represented among the settlements that were dropped, as they comprise 27.81% of the 187 total settlements dropped despite representing only 12.84% of all 1036 settlements. Nevertheless, the within-type proportions indicate that all settlement types were considerably affected.

Notably, figure 5.8A shows that between the years 2015 and 2016, every settlement type experienced a pronounced decrease in their respective proportions of settlements with access to sources of each class. Slightly less pronounced but notable decreases are also visible for the years 2000 and 2001 and 2018 and 2020. These correspond to the periods in which there were sharp increases in median distance to the *high extent - high frequency* class, particularly for the *disappearing* and *emerging* settlements (see figure 5.6). During these periods, there may have been a more widespread and accelerated expansion of agricultural landholdings, though I cannot identify the exact drivers behind this increase in activity along the frontier.

Figure 5.8B offers further confirmation that settlement distances to sources of the *high extent - high frequency* class tended to increase the most over time. The settlements that were dropped saw a higher median difference in distance to sources of this class than for the other saturation classes. The 3rd quartile is also considerably higher than the other classes, indicating that there is a wider range of sources in this class that were further from settlements in the last year than in 2000. Therefore, these are clearly shared qualities between the settlements that were dropped and those that were constant.

Like the settlements that were constant, the settlements that were dropped also had the second highest median differences in distance to the *high extent - low frequency* class, which suggests that this class was less accessible than the *low extent - high frequency* class. However, the settlements that were dropped had a lower median difference in distance to sources in every saturation class between 2000 and the last year they remained in the sample. This indicates that before their enclosure, they maintained slightly more access to surface water overall compared to their counterparts.

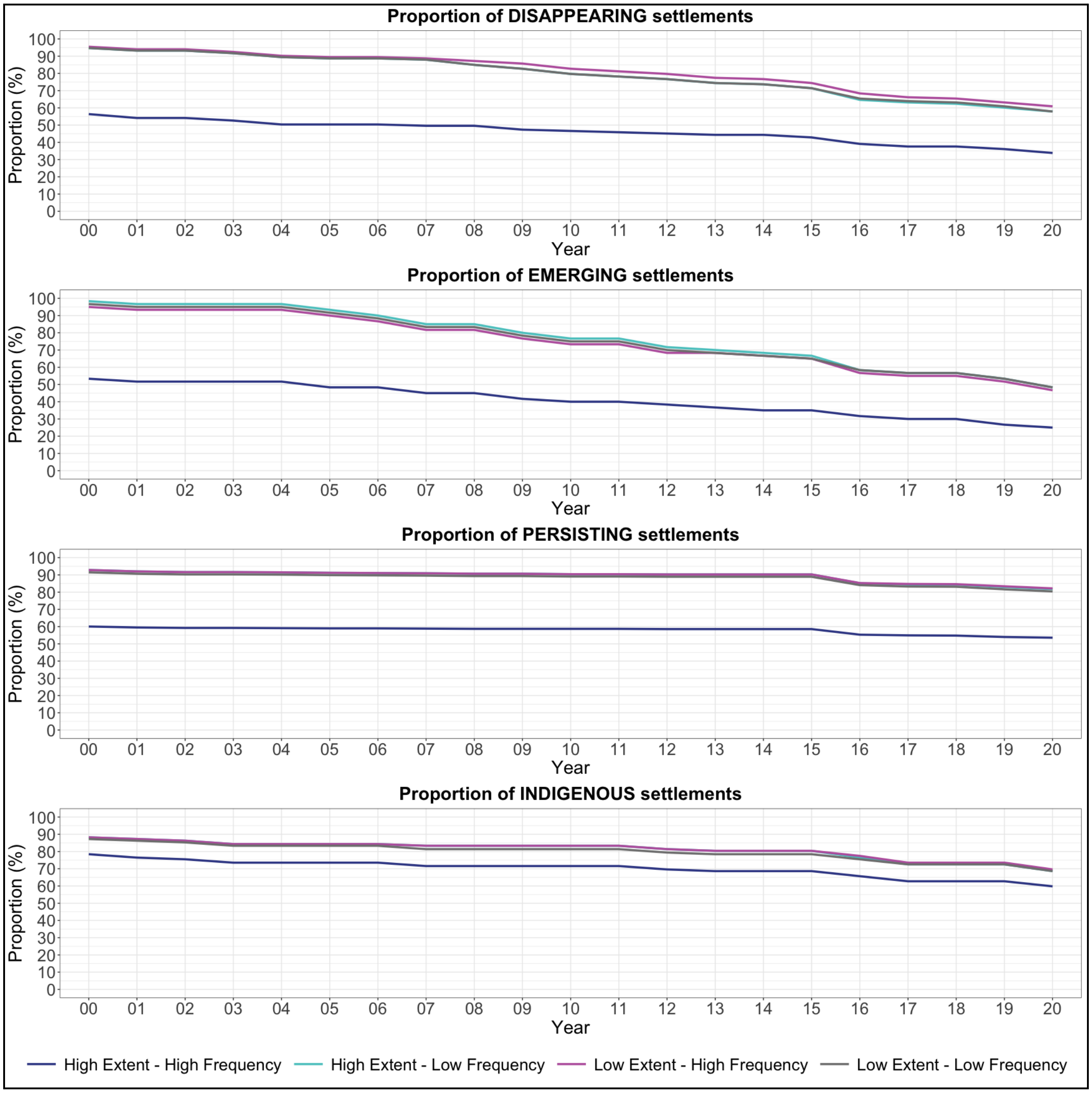

Figure 5.8A. The annual proportion of settlements in each settlement type with a source of each saturation class within 15 km. Decreasing trends indicate that settlements were dropped from the sample due to becoming directly enclosed by agricultural landholdings.

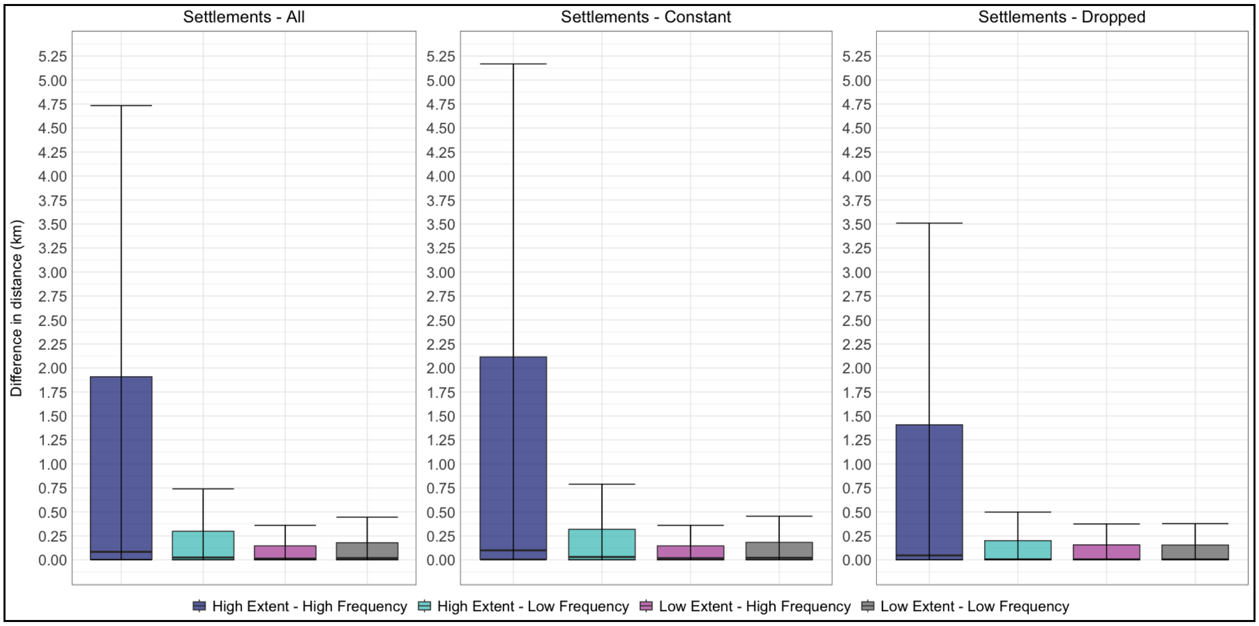

Figure 5.8B. The statistical distribution of the difference in distance (km) from the year 2000 to the last year in which a settlement was included in the sample. As the name states, the settlements - all *includes every settlement, the* settlements - constant *includes only those settlements that remained in the sample for all 21 years, and the* settlements - dropped *represents settlements that were present in 2000 but dropped from the sample before 2020.*

5.9. Chapter conclusion

This chapter reviewed the key findings from my analysis. I first highlighted results from the surface water classification, showing that the *largest - low extent - high frequency* class is the most widely distributed class and the most likely to be encountered across most of the basin given its natural spatial extensiveness. My results also revealed that the *high extent - high frequency* saturation class is among the least widely distributed and also the least likely to be encountered of the four saturation classes, indicating that the availability of the most useful surface water for livelihoods is geographically limited.

I then outlined the most important takeaways from the access analysis. First, I identified the settlements that lost access to different surface water classes between 2000 and 2020 and those that experienced transitions from their closest source of surface water being one class to a different one, including loss of access to all surface water sources altogether. I also reviewed patterns among the settlements that did not experience transitions during the 21-year period. *Emerging* and *disappearing* settlements had the highest proportions of settlements losing complete access to surface water, though the case of the former is probably most attributable to errors in the land cover/land use data.

My focus then shifted to the annual changes in distance to different saturation classes among the four settlement types. I found that across all settlement types, the median annual distance to each of the four saturation classes was increasing over time. Of even more concern is that the overall median increase in distance to the *high extent - high frequency* class, the most useful one to livelihoods, was higher than for any other saturation class for all settlement types. These findings indicated that not only was access to sources of different surface water types becoming more challenging, the most useful type of surface water was becoming less accessible at a faster rate across all settlements, with the *disappearing* settlements losing access the fastest relative to its counterparts.

In the final section of my review of results for the access analysis, I described how the direct enclosure of settlements resulted in their exclusion from the previously reviewed portions of the analysis. Here, once again, it was the *disappearing* settlements that displayed the highest vulnerability to the effects of the expanding frontier, but the other settlement types also show concerning trends. This is particularly true for the *Indigenous* type, which saw 20.59% of its settlements enclosed by 2020. Therefore, there are several important insights to draw from these results. In the next chapter, I discuss the implications of my findings as well as some of the limitations of the analysis.

CHAPTER 6. DISCUSSION

In this study, I adopted a livelihood-centric approach to classify surface water in the Pilcomayo basin to capture spatial-temporal features (the extent and frequency of saturation) of surface water that are relevant to supporting inhabitants' livelihoods across the region, including beyond the riparian zone. I used the results of this classification as inputs in an access analysis to determine to what extent accessing different types of surface water is becoming more difficult for rural populations as the agricultural frontier expands across the landscape. Through these two stages of analysis, I illustrate how different types of surface water sources that are physically within range of rural populations' settlements have become less accessible to them due either to the direct enclosure of the sources themselves or to the blocking and the enclosure of pathways leading to them. In the following sections, I discuss the key insights that emerged from the results of the surface water classification and access analysis.

6.1. Distribution of surface water in the Pilcomayo basin

My classification offers insights into the physical availability of surface water throughout the region, revealing interesting associations between size, saturation frequency and saturation extent.

Regional differences in the distribution of surface water. First, at the level of climatic subregion, there are fewer surface water sources of all classes in the Dry Chaco than in the Humid Chaco, despite the latter covering a smaller surface area than the former. Second, there was a pronounced absence of geographic clustering of the *small* surface water sources in the northernmost portion of the basin. The close association of this size class with the *large* size class could be contributing to this distribution pattern. While several of the *small* sources are easily identifiable as stock ponds, visual inspection also reveals that there are a considerable number that seem to be disconnected portions of *large* size sources, such as the meandering sections of intermittent streams for which the segmentation and post-segmentation processing could not properly capture connectivity, as well as areas of intermittent flooding near a variety of *large* sources. In general, the concentration of the *large* sources is less dense in the north of the basin, with the exception of a cluster visible in the north Central Chaco; therefore, it may be that the lower concentration of *large* sources in the north reduces the probability of *small* sources' occuring in the area since one would expect less flooding in these areas. However, given the uniformity of the absence of *small* sources in the northernmost region of the study area, the most probable cause seems to be errors in either the detection of surface water itself, or in the manner that the segmentation and post-segmentation algorithms grouped pixels in this subregion.

Association of size and frequency classes. The fact that the *small* size sources of surface water were considerably more likely to fall in the *high extent - low frequency* classes more than their two larger counterparts also indicates that their small size may have worked "against" them in achieving higher levels of temporal stability (reflected in the frequency). The majority of the *small* size sources were a single pixel, and, as such, they could not have a low extent. In addition, the *small* sources occuring within the riparian zones of rivers and in close association with other *large* sources are likely small zones of occasional flooding, making them more likely to be ephemeral than the channels and depressions that fed them. Consequently, one would not expect to see a high frequency of saturation throughout the temporal archive for many of these sources. If these *small* sources truly do represent areas of periodic flooding, this could also explain why some of the observations identified as surface water do not look like areas in the landscape that would regularly retain water. However, mere visual inspection of satellite imagery cannot confirm this, especially for some examples that appear to be quite spatially distant from any other source of surface water that could flood the area. In most cases, there is likely slight topographic variation in the landscape that is not immediately visible through imagery, thus requiring a DEM to more accurately assess the probability of the depressions throughout the landscape contributing to this phenomenon. In other cases, especially in the northern region where *small* sources are absent, it is possible that technical errors in the detection or even in the segmentation and post-segmentation algorithms played a role in their being accepted as valid observations.

In contrast to the *small* sources, the *large* ones are more likely to fall in the *low extent - high frequency* class. Operating inversely to their smaller counterparts, the *large* sources likely experience a lower saturation extent overall because their more extensive surface area reduces the probability that all pixels will hold water at the same time. On the other hand, the greater surface area of these sources permits that they are more likely to be captured at the temporal scale of frequency of saturation, as only one pixel needs to hold water for the object to have some level of valid "saturation".

6.2. Considerations in classifying and characterizing surface water

Other approaches to livelihoods-based classifications of surface water in the literature and contributions of the thesis. Other surface water classification schemes that authors have carried out in various river basins throughout the world rely on climatic, geomorphological, hydrological, and even hydro-ecological variables to define different types of surface water, including rivers, lakes, and estuaries (Ouellet Dallaire et al., 2018). Such classifications are useful in understanding the physical availability of surface water as a result of processes that often link to but also extend beyond the frontier dynamics at work in the region. In particular, river classifications that aim to define rivers' flow regimes can provide insight into the River Pilcomayo's short and long-scale temporal fluctuations and spatial patterns. However, studies describing surface water distribution with respect to rural livelihoods rarely classify the sources of surface water of interest. For example, although they were not explicitly classifying surface water in the region, Ritter (1975), Iriondo et al. (2000), Martín-Vide et al. (2012), and Baigún et al., (2012) all highlight aspects of the Pilcomayo and its associated wetlands that greatly impact these sources' capacities to support rural livelihoods. Correia (2022), on the other hand, calls attention to a critical dimension of surface water that directly impacts both livelihoods and human health directly: water quality.

Iriondo et al. (2000) approach the Pilcomayo from a paleo-geomorphological perspective, providing the historical context for not only the river, but the basin as a whole by characterising the alluvial fan (sediment deposits formed as flowing water comes into contact with topographic features of the landscape) that defines the boundaries of the Pilcomayo basin. The geomorphological history of the basin as a whole has shaped the current topography of the region which, in turn, has implications regarding where surface water can be found throughout the landscape. Human influence on this landscape, or the "waterscape", as Correia (2022) refers to it, is also an important component of this geomorphological and hydrological history, as Correia (2022), Ritter (1975), and Martín-Vide et al. (2012) demonstrate. Ritter (1975) and Martín-Vide et al., (2012) take a somewhat similar approach in centering the hydrological and geomorphological attributes of the river, with particular attention to its high sediment load and the consequences of this in terms of the river's movement. Both specifically include the anthropogenic dimension in their discussion of the river's behavior, with Ritter (1975) citing mining operations upstream in Bolivia as potentially accelerating the geomorphological processes contributing to the river's retreat upstream and Martín Vide et al., (2012) delving into the river's shifting morphodynamics in conjunction with artificial channels. Correia (2022), however, explains how the persisting legacy of settler colonialism, especially in the form of the expansion of cattle ranching, has altered the distribution of (and access to) surface water in the form of stock ponds and earthen tanks, with fences as the means of controlling access.

In contrast, Baigún offers a hydro-ecological perspective in describing the Pilcomayo River by discussing how a proposed dam could alter the hydrological regime of the river and, consequently, the migration of the *sábalo* (*Prochilodus lineatus*), a fish with high subsistence and commercial value to Indigenous and mestizo populations. This would fundamentally change the river's flow, and even if surface water itself continues to be available to some extent, the way that this source of surface water is used could fundamentally change if it becomes less capable of providing fish for consumption and commerce. While this particular example is specific to the river, lentic surface water can also be assessed from a human ecological perspective. For example, depressions in the landscape that periodically fill with water can serve as important gathering grounds for wildlife seeking hydration, which, in turn, could then impact how rural populations that practice hunting track animals.

Although these authors do not have the stated goal of directly "classifying" surface water in the region, they provide essential context for several interconnected processes that simultaneously impact and are impacted by the acceleration of the agricultural commodity frontier and the practices that rural populations adopt in response to the natural variability of surface water in conjunction with the increasing anthropogenic pressure at various scales. Their approaches to characterising the Pilcomayo river, its associated wetlands, the basin, and surface water overall provide different means of discussing how surface water within the landscape connects to history, wildlife, people, and politics. These serve as important background for understanding current surface water dynamics that impact the distribution of surface water, but could also be used directly to classify surface water. For example, classes could be defined based on whether a source falls within an area of active deposition; whether specific fish species are supported by the aquatic ecosystem; whether a dam has been built upon a particular branch of the river; or whether the source is artificial, natural, or some combination of both. These are just a few potential "classes" of surface water that could be formed depending on the primary objectives in forming the classification. However, these approaches to discussing surface water do not provide systematic information regarding the availability of surface water that can support different rural livelihoods. Additionally, their scope is limited primarily to the river itself and the wetlands directly associated with it.

The spatial-temporal features (the extent and frequency of saturation) that my classification highlights capture attributes of water that have more direct implications for livelihoods across the Pilcomayo basin. For instance,fishing livelihoods along the Pilcomayo River also depend on annual flooding to feed the riparian zones of the river and provide habitat for key fish species such as the *sábalo* (Brown et al., 2018). The classification also captures dynamics that extends well beyond the riparian zone of the Pilcomayo River. For communities living beyond the Pilcomayo River and its associated wetlands, smaller surface water bodies, even those that may only infrequently hold water, are vital in supporting their livelihoods. Therefore, extending the analysis beyond the river and its associated wetlands captures water bodies such as ponds, ditches, and intermittent streams, all of which support aquatic and terrestrial species of plants and animals (Biggs et al., 2017). Livelihoods centered on hunting/gathering, apiculture, and wild honey collection can benefit from relative proximity to any kind of source of surface water that wildlife could use for drinking water. Likewise, livestock-based livelihoods require that surface water be available within range of the smallholder settlement or community.

It is worth noting, however, that proximity to water is not unequivocally positive. In particular, proximity to large sources of surface water that are prone to flooding simultaneously introduces risks and advantages for sedentary livestock herders. On the one hand, their settlements can be threatened by rising water levels in the wet season, and pathways can become inaccessible, yet the flooding is also important in feeding wetlands and filling surrounding topographic depressions with water (Baumann & Cavallaro, 2008). These are additional sources of water that may remain into the dry season as well, and they also support biodiversity (Biggs et al., 2017).

Possible improvements to this approach. Other approaches to surface water classification would also help to elucidate how surface water has been changing alongside the regional acceleration of the agricultural commodity frontier as well as the global scale of climate change. For instance, with a more robust archive of higher resolution imagery now available from the 2010s onward through Sentinel-2 and Planet Labs Satellite Imagery, a segmentation of the surface water based on the higher resolution imagery from the last decade would add further context to the classification. This could increase the quality of the connections between objects, reducing the number of unlinked portions of objects representing long, meandering streams and extensive wetlands. Additionally, although I believe a classification across the full period was ideal for the purposes of my investigation, classifying surface water by periods would provide interesting insight into the emergence and disappearance of surface water over a longer period of time. A narrowed temporal window could also unveil the seasonal patterns in the expansion and retreat of the sources of surface water throughout the year. This, however, requires a more explicit exploration of the potential impact of the fluctuations in the "natural" physical distribution of water (rather than the influence of the agricultural commodity frontier alone) in examining patterns of emergence and disappearance of settlements.

6.3. Implications of surface water distribution for access to surface water

The results display several patterns that help capture the complex circumstances that shape surface water distribution and, by extension, rural populations' access to surface water amidst the expanding agricultural commodity frontier.

Availability of surface water for livelihoods is lower in the Dry Chaco, making them more vulnerable to changes. At the level of climatic subregion, there are fewer surface water sources of all classes in the Dry Chaco. This indicates that gaining access to surface water in this subregion is inherently more challenging considering that the number of sources viable to support rural livelihoods throughout the year is limited by a relatively higher scarcity of water than in the Humid Chaco subregion. As such, any restriction in accessing surface water in the Dry Chaco could quickly throw a rural smallholder's livelihood into a precarious state and shift the dynamics of the livelihood's vulnerability context. In particular, the increased pressure from agricultural landholdings may intensify the impacts of seasonality and the naturally limited physical availability of surface water in the region.

Diversity of available water sources matters. Although the *large* sources of surface water tend to display higher temporal stability relative to that of the other size classes (i.e., there is a greater proportion of the *large* sources that fall in the *low extent - high frequency* class), because they are more spatially extensive, it is more difficult to interpret the impacts of any amount of drying that they may experience since the spatial extent of dryness may not affect all rural populations equally. For instance, if a spatially extensive wetland dries in 50% of its total potential surface area during the dry season, the remaining 50% of saturated area may occur beyond reach of a settlement located closer to the dried portion, while people inhabiting the saturated area may not be negatively impacted at all. As a result, even if the majority of surface area that a large source comprises remains accessible, any relatively "small" portion of it surrounded by agriculture or cattle ranching effectively results in a loss of access for those rural populations whose settlements occur closer to the inaccessible portions, and the reverse scenario is also true. These scenarios further illustrate that rural populations benefit most from having access to a *variety* of surface water sources. That is, access to a range of sources with diverse spatial-temporal patterns of saturation allows a rural inhabitant to migrate to viable sources throughout the year, particularly during the dry season or prolonged periods of drought, once other sources are too dry. However, my findings suggest that the expanding agricultural frontier tended to reduce rural populations' overall access to a variety of sources of surface water. Consequently, the expansion of the agricultural commodity frontier in the region may have corresponded to a decrease in the sustainability of rural livelihoods not only during dry periods, but throughout the entire year.

The most useful types of water are the least accessible, and the ones experiencing the greatest accessibility decrease. The lower abundance and likelihood of encountering sources of the *high extent - high frequency* saturation class (arguably the most "useful" to livelihoods) across the region likely contributed to these sources becoming inaccessible at a faster rate than those of the other saturation classes. This saturation class consistently experienced the highest median magnitude of change in distance over the 21-year period for all settlement types. This finding shows that rural populations have lost access to the surface water sources that hold water more consistently throughout the year compared to other sources. Loss of access to this surface water class may leave rural populations' livelihoods in particularly precarious states during the dry season, when surface water is even scarcer.

Another possible explanation for the faster rate of decline in access to high extent - high frequency water sources is that large-scale ranchers may have been more attracted to these relatively stable sources of surface water and constructed their landholdings around them in order to secure their own private access to them for their livestock. Likewise, the landowners may themselves have mandated the construction of stock ponds on their property (Correia, 2022). If these generally retained more water than other sources, they may have become the only stable sources of water for some rural populations. This is true for three Enxet and Sanapaná Indigenous communities of the Bajo Chaco. These communities rely on stock ponds originally built for cattle that were left by the ranchers and that now serve as these populations' sources of water for drinking, cooking, and bathing, though it is important to note that the water quality of such sources is very low, so people only use them because so few (if any) other viable options are consistently accessible to them (Correia, 2022).

6.4. Links between settlement temporality and access to surface water

A significant advantage to having access to the settlement types defined by their temporality was that it allowed me to explore potential correlations between settlement temporality and access to surface water sources, in particular to the *high extent - high frequency* saturation class. Indeed, these correlations materialized in the results. Each settlement type displayed particular patterns linked to their geographic location relative to certain types of surface water and to subregional or localized waves of cropland and pasture expansion.

Settlements that disappeared during the study period were also ones that had higher water access loss. Other than to the *low extent - high frequency* saturation class, the *disappearing* settlements experienced the highest rates of increase in distance to saturation classes. They also experienced the second highest increase in loss of access to surface water classes altogether (I briefly address the *emerging* settlements' taking first place for this phenomenon later in this section). The greater rate of increase these settlements experienced suggests that they occur in locations that experienced a slightly more rapid and aggressive encroachment of private landholdings. Though I cannot demonstrate that this is a causal link, my findings suggest an association between settlements disappearing and the loss of water access associated with agricultural land expansion. More specifically, it is possible that since the *rate* of agricultural expansion was higher around these settlements, the inhabitants may have directly observed an accelerated period of enclosure.

In focusing on water and using agricultural landholdings as the sole proxy for access loss, my analysis could not fully capture the other dynamics at play that are indirectly linked to rural populations' access to surface water. Enclosure of land effectively reduces the area that rural inhabitants and the animals that they rely on can move freely within, consequently reducing wild animals' and livestock's access to resources necessary for their survival – namely forage and water (Cáceres, 2015). This may push rural inhabitants to shift to other livelihood strategies that can be managed on smaller areas of land, such as shifting from cattle and goat rearing to pig rearing (del Giorgio et al, 2022).

Even if a property demarcation is physically passable, "trespassing" can have dire consequences. Landowners can be very strict in monitoring their property lines, with some going as far as shooting animals that pass into their property, hiring armed guards to patrol property boundaries, and intentionally running over livestock that graze along the sides of roads (del Giorgio et al., 2022). Because of the threat of such violence, rural inhabitants are forced to adapt in ways that may reduce the sustainability of their livelihoods, such as by reducing the number of livestock that they tend to in order to manage them on smaller areas of land (Altrichter & Basurto, 2008). In the most dire circumstances, the pressure from the encroachment may even displace the rural inhabitants all together (Cáceres, 2015), which may even form part of the narrative for the *disappearing* settlements in my study. Only a comprehensive local study would be able to confirm dynamics such as these, however. Therefore, my interpretation of the results of my analysis are limited to the direct observations of other authors who examined the dynamics and processes that my analysis cannot confidently elucidate.

Settlements that remained stable experienced less water access loss but their water access may be threatened if agricultural expansion continues. Considering the other settlement types appear to be experiencing a more gradual decline in access to surface water, the urgency of the circumstances surrounding access may be slightly more remote for them. That is not to say that these inhabitants are unaware of their potentially precarious situations, but rather that the process of enclosure has been occurring gradually enough that they can weigh their options and perhaps even gather some defenses against the encroachment (for instance, by pursuing titles to their land). In other cases, the threat may simply not have arrived, as regions north and south of the upper portion of the Pilcomayo River have not been as rapidly developed as other regions such as the Central Chaco.

The *persisting* settlements' overall retention of surface water classes through time, lower proportion of transitions in the closest class from 2000 to 2020, and near absence of high fluctuations in median distance to all classes indicate that these settlements have not been impacted as extremely as their counterparts. Given that these are the settlements that have been around the longest, their patterns in access change also support the hypothesis that access to surface water and the temporality of settlements are linked. Nevertheless, these settlements did, of course, experience impacts from the land use changes as well. Arguably, if the trajectory displayed in my findings continues, these settlements may continue to experience gradual declines in access to surface water that slowly put these settlements in danger of eventually meeting the same fate as their *disappearing* counterparts.

Indigenous settlements retained access to most water sources but lost access to some of the more useful water, and may be affected by the proximity to ranches. The *Indigenous* settlements are an interesting case, as many of the settlements are located in the Central Chaco where waves of intensive agriculture and extensive ranching has been taking place since at least the mid-20th century with the rise in cotton cultivation, particularly among Mennonite farmers (Vázquex, 2013, p. 97). Indigenous settlements' close spatial proximity to the Mennonite communities began around the start of the Chaco War, when they were forced to establish sedentary settlements and work in sectors such as agriculture (Hirsch et al., 2021).

These settlements lost all sources of the *high extent - high frequency* as their closest ones by 2020 and experienced an overall increase in median distance of 1.50 km to sources of this saturation class by 2020, both of which indicate that *Indigenous* settlements are losing access to the most useful sources of surface water around them. On the other hand, most of the settlements displayed relative stability in terms of retaining access to the same diversity of surface water classes and to some form of surface water overall. Taken as a whole, these findings suggest that

Indigenous settlements have retained access to surface water in spite of the advancing frontier, but not necessarily to a wide variety, nor to the most useful types. In addition, considering that many of these settlements are close to ranches and agriculture, the sources of surface water to which they retain access may be heavily polluted with animal feces, pesticides, and fertilizers (Correia, 2022). This settlement type's geographic and historical circumstances aptly illustrate why assessing different *types* of surface water, rather than simply surface water as a whole, is important when discussing access, as not all surface water sources will be as useful (though my classification also falls short of capturing other important attributes such as water quality, as reviewed in section 6.2).

Results for settlements that emerged during the period are dominated by mapping errors. The *emerging* type held the fewest number of settlements but had the highest concentration of settlements (50.00%) in an area of the basin in which the land cover/use dataset could not reliably differentiate cropland and pasture from natural land cover types (section 6.6.2 explains this issue in more detail). As I pointed out in chapter 5, it is likely that the access loss and the proportional loss of surface water classes were both overestimated for the *emerging* type. However, despite this error, there are some key points to consider for these settlements. To start, considering that so few settlements compose the *emerging* type, the clustering of half of the settlements in the sample along this specific region of the Pilcomayo begs the question of what factors played into the inhabitants' decision to settle there. From my analysis, it is uncertain what factors may have led to the emergence of these settlements in their specific respective locations. Since I cannot reliably interpret the values of changing distance over time for these settlements, it is unclear the degree to which access to different surface water classes drove the emergence of these settlements. It is possible that the correlation would not have as much to do with seeking access to sources of specific classes so much as seeking areas where the frontier has not advanced as aggressively, which, by extension, would show higher access to surface water. Therefore, elucidating the specific drivers of emergence of settlements across the basin would require local interviews with the inhabitants of these settlements, a detailed spatial regression model, or a combination of both for a highly comprehensive perspective.

6.5. Comparing approaches to estimating changes in access to natural resources

The land cover/use data to approximate areas of access loss allowed me to assess changes in access across an extensive geographic area. My approach is similar to that of Yu et al. (2019), who used a cost distance calculation based on land cover and slope data to measure access to surface water sources in Kenya. However, their proxy for access was walking time rather than distance in kilometers. Additionally, they limited the scope of surface water sources to those used explicitly for household domestic use, excluding sources that may be used primarily to support livestock, for instance. My approach, in contrast, is primarily concerned with sources used to support livelihood activities, some of which may include household domestic use, such as being able to water a vegetable garden, and much of which would directly involve supporting livestock. I also consider the indirect benefits of proximity to surface water, such as its capacity to attract wildlife that rural populations opportunistically or strategically hunt.

In the geographic context of the Gran Chaco, del Giorgio et al. (2021) applied the cost distance model to assess the impact that fences and roads have on the mobility of smallholders and the different livestock (cows, pigs, and goats) they keep. There are other forms of access measurement that do not use a cost distance algorithm but still rely on land cover/use data. For example, Buzzard et al., (2022) incorporated land cover/use data along with data on roads and land ownership boundaries to map the locations of fences in southwest Montana, USA. These studies also operated at different scales: Del Giorgio et al. (2021) and Buzzard et al. (2022) measure access at local scales that allowed for ground-truthing, while Yu et al. (2019) and my own study assess access at a larger regional scale, reducing the feasibility of rigorous ground-truthing but allowing for the identification of landscape-level and long-term trends.

6.6. Limitations

6.6.1. Limitations to the classification process

The segmentation process that generated the objects representing surface water does not perfectly identify and unite what are clearly spatially contiguous sources of surface water in the true landscape. This can cause the potential issue of splitting what is logically a spatially contiguous source of surface water into smaller objects. This seems particularly pronounced for those objects that represent narrow, meandering streams, as their complex forms were more difficult to capture within a single contiguous object for both the segmentation and the post-segmentation algorithms used to join the two segmentation iterations.

The subsequent classification of the objects representing surface water formed from the segmentation is quite broad, which offers an appropriate overview of the spatial-temporal tendencies of different sources of surface water but also omits or obscures attributes only identifiable through the inclusion of other variables or a finer scale spatial-temporal resolution. Therefore, although one can generally discern through visual inspection what "real" types of surface water sources in the landscape tend to fall within each of the defined surface water classes, my classification does not explicitly differentiate classes of *river, wetland, lake, stream*, etc., as these are defined by more precise hydrological, geomorphological, and ecological attributes. Even for the parameters that I defined for the classification, there are clear limitations to the capacity for the classification to group sources of surface water that share similar physical characteristics. For instance, the *large* size class included the main branch of the Pilcomayo river, with a total approximate surface area of 763 km^2, but it also included sources of less than 0.5 km^2. This means that even with the size classes, the saturation thresholds are being applied to objects with spatial extents that can vary considerably. However, given that the size classes as they were defined yielded results that overwhelmingly skewed *high extent* - *low frequency* values to the *small* surface water sources and strongly skewed the *low extent - high frequency* to the *large* sources, the size differentiation still highlighted significant correlations between size and the saturation classes.

As for the explicitly spatial-temporal component of the classification, defining an individual source's spatial-temporal tendencies by the sample mean of the extent and frequency across the 21-year period generates its own set of limitations as well. It is also unclear if some of the surface water sources within the *low extent - low frequency* classes may have been temporally stable for an extended period, but then began to reduce in spatial extent and ultimately completely disappear at some point in the temporal archive. The alternative process may also be true: that is, some surface water sources could emerge later in the temporal archive and, simply as a result of having existed for fewer years, may have a lower temporal frequency, resulting in a *low* frequency specifically. As explained in section 4.2, I assume that the majority of naturally-occurring sources, especially the *large* and most of the *medium* size ones, are unlikely to have fully disappeared or emerged during the time period between 2000 - 2020 since most of the most significant hydrological changes occurred prior to this period. Nevertheless, it is possible that some of the *small* and even some of the *medium* size surface water sources may have emerged with the development of the region, as these classes include a considerable number of stock ponds. As medium and large-scale agricultural activity has accelerated in the region in this time frame, it is possible that these stock ponds were constructed at a later time point when these developments began to take off.

This raises another key component of surface water that my classification does not capture: water quality. Forms of surface water such as stock ponds may be acceptable for livestock's consumption, but these are unlikely to count as potable water sources that meet human health standards due to contamination of these sources from the fertilizers and other chemicals used on agricultural land (Correia, 2022). These fertilizers can also result in the salinization of surface water sources (Kaushal et al., 2018). Additionally, several studies have shown that the conversion from natural vegetation cover to agriculture results in the water table rising, which can eventually result in surface salinity increasing (Giménez et al., 2016; Marchesini et al., 2016; Jobbágy et al., 2020; Rodríguez et al., 2020). Researchers have also demonstrated that the Pilcomayo River has suffered from heavy metal contamination from the mining activities upstream of the Chaco in Potosí, Bolivia (Strosnider et al., 2014). Therefore, water quality is a critical dimension to consider to gain a more complete perspective on the state of surface water access for different communities in the Gran Chaco based on how they use it. In situ soil and water quality testing of surface water bodies as well as the detection of algal blooms using remote sensing assessments are two examples of effective methods that could inform the state of water quality at the local and regional scales, respectively. These approaches would be especially useful to analyze small water bodies in the region beyond the floodplain of the Pilcomayo. Historically, small water bodies have been largely ignored in hydrological research due to challenges in mapping them because of their size, but recent research has shown the potential of mapping and monitoring these surface water bodies more precisely with Landsat and Sentinel-2 data (Ogilvie et al., 2018; Dong et al., 2022).

6.6.2. Limitations to the access analysis

A first set of limitations is related to the remote sensing data used in this analysis. Although Baumann et al.'s (2022) land cover maps are effective in capturing demarcations of developed cropland, they do not identify narrower strips of deforested land contiguously, which leaves. For instance, the maps do not consistently capture fenced, narrow corridors between areas of natural land cover directly alongside private property. Consequently, my results may slightly overestimate the permeability of areas of the landscape in areas where natural land cover is in close proximity to private property.

In addition, the data misidentified regions of frequent flooding along the river as agriculture and pasture. Flooding creates natural disturbances that alter the landscape in ways that can be difficult to interpret solely from satellite imagery. While visual inspection of high-resolution satellite imagery confirms that there are areas of cropland and pasture in these regions, it also shows that the algorithm used to create the dataset misclassified many of the pixels in this region, possibly due to the frequent flooding disturbances. The effect is especially pronounced in the area just upstream and along the *pantalón* division of the River Pilcomayo, and settlements of all types with 15 km radii that overlapped with this region showed high percent decreases in their surface area covered by surface water. Thus, the spatial clustering of the *emerging* settlements along the *pantalón* division greatly influences the results yielded for this settlement, as discussed in section 5.3.

A second set of limitations also relate to the overestimation of access loss, though specifically with respect to my baseline assumptions regarding who is converting land from natural land cover to agriculture and pasture. For my analysis, I assumed that medium to large-scale landholders were the ones using the land identified as cropland and pasture, and that it was therefore fenced and inaccessible to smallholders, as I could not feasibly distinguish land us by smallholders and Indigenous communities from that of actors operating on larger scales for the entire region. However, I do not believe that the overestimation of accessibility is widespread across the full region, as the plots appear too large to be from smallholders in high-resolution Google Earth imagery.

The third set of limitations concerns the temporal scale of my analysis. With respect to the settlements, my time period of interest (2000 to 2020) is somewhat dissonant with that of the dataset for the *disappearing, emerging*, and *persisting* settlements, as the Levers et al. (2021) dataset only tracks them until the year 2018. In addition, my surface water classification does not capture seasonal and interannual changes in the surface water sources, nor does it capture sources that may have appeared or disappeared later in the time period. This means that there may be cases where a surface water source was physically absent from the landscape despite my analysis indicating that it was accessible. Nevertheless, the goal in generating this classification was explicitly to capture broad, landscape-level changes in surface water sources, and, as described in section 4.2, widespread hydrological changes seem unlikely to have taken place across the basin during this time period.

Finally, my study's extensive regional and temporal scope and the methodological focus solely on distance to surface water cannot capture the local social, political, cultural, and institutional dynamics that are key in determining rural populations' access to surface water. Consequently, my assumptions regarding what factors drive the disappearance, emergence, and persistence of settlements are limited since the analysis does not include the perspectives and experiences of rural inhabitants of the Pilocmayo. Furthermore, I cannot confirm that reduced access to surface water as a result of expanding agriculture directly caused the abandonment of *disappearing* settlements, nor that *persisting* settlements remained due to their better access to a diversity of surface water sources. It is possible that in some cases, the *disappearing* settlements may have moved as a result of encroachment of the river's flood waters. In fact, even some of the current Indigenous settlements such as San Agustín were established after abandoning the former settlements located closer to the river because of the imminent threat of flooding. In these situations, the presence of *too much* water drove the migration, but such contexts are limited exclusively to the riparian zone of the Pilcomayo River. Field surveys, interviews with the local populations of the Pilcomayo, and analysis of land ownership/land tenure documentation would provide more reliable and comprehensive insight into the extent to which access to surface water contributes to the decision and ability to either stay or migrate. Such qualitative research is also necessary to uncover the structural and relational mechanisms of access and power dynamics that impact the feasibility of different livelihood strategies.

CHAPTER 7. COMPREHENSIVE CONCLUSION

My objectives in this study were to broadly identify the distribution of surface water classes according to their spatial-temporal tendencies across the Pilcomayo basin to then elucidate how this distribution overlaps with the expansion of agriculture in the region and ultimately dictates the conditions of access to surface water for rural populations. In the classification of surface water, I focused on attributes of surface water (size; spatial extent; and frequency) that highlight their usefulness to livelihoods such as livestock production, hunting, fishing, and honey production. Though not all surface water sources support all livelihoods, I generated the classification with the assumption that any source of surface water within the classification had the theoretical capacity to support at least one form of livelihood.

While the way that climatic, hydrological, and, occasionally, infrastructural variables interact determines the physical distribution of different types of surface water in the Pilcomayo basin, anthropogenic factors dictate the accessibility of surface water in the region. To assess how access to different types of surface water has been changing over time across the Dry Chaco portion of the basin, I compared the annual minimum distance, in kilometers, from human settlements to the nearest surface water source of each surface water class from 2000 to 2020. I interpreted the presence of cropland or pasture as a proxy for loss of access, as private landholdings are fenced in before they are converted to croplands or pastures, and fences act as a physical barrier that enforces the exclusion of local inhabitants. I demonstrated how even very small, localized spatial changes can have consequential impacts in the distances that a rural inhabitant must travel to avoid trespassing on private property.

My methodological approach allowed my analysis to extend across a spatially expansive area and glean key insights into the broad geographic patterns of surface water availability. The segmentation algorithm used in the first stage of the surface water classification enabled me to represent surface water as individual bodies of water with different potential uses for livelihoods. Through the access analysis, I was able to demonstrate and characterize changes in access across the basin, and focusing on specific settlements allowed me to incorporate a more realistically local perspective rather than assessing access changes from random points within the landscape. Furthermore, the stratification of the settlements allowed me to identify patterns of temporality that would not have been visible otherwise. Local, qualitative political ecology research has been the traditional avenue to gain comprehension of such dynamics and patterns, and while my approach certainly does not replace this, it serves as a comprehensive complement to it.

Thus, my analysis illustrated how large and medium-scale private agricultural landholdings, by acting as barriers that restrict the mobility of people and animals alike, reduce their access to a variety of surface water sources, particularly those that are most useful to livelihoods. In fact, I found that the most useful sources were the most likely to experience the highest increases in distance to the settlement of interest. Furthermore, although my findings did not confirm any causal links to specific mechanisms that drive the temporality of settlements, the results evidenced that the overall loss of access to a diversity of surface water classes and to the most spatially-temporally stable sources was associated with the disappearance of settlements.

To conclude, this study demonstrated the ways in which the distribution of surface water across the basin and the expansion of the agricultural frontier shape the complex landscape of access that rural populations navigate in both literal and figurative terms. Though access is often framed with respect to land, my findings show that the same dynamics also apply to surface water. In the same way that different areas of land possess different livelihood-specific natural resources, different sources of surface water have particular attributes that allow them to support livelihoods in unique ways. This study also contributes to the body of literature that details how agricultural commodity frontiers tend to perpetuate exclusion and marginalization of Indigenous peoples and smallholders. Without the protection of Indigenous and smallholder land in conjunction with firmly enforced caps on the maximum area of land that can be converted for agriculture, rural inhabitants may continue to face troubled waters in the wake of the expanding frontier.

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