# DAMS IN THE AMAZON: SOCIAL AND ENVIRONMENTAL IMPACTS ON BASIC SANITATION, PEOPLE, AND THE ENVIRONMENT

By

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**ABSTRACT**

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Hydroelectric projects continue to be built in the Amazon, Congo, and Mekong Basins to harvest hydroelectric potential and increase energy security, economic growth, and industrialization. In Brazil, heavy investments in hydroelectric developments are occurring throughout the Amazon Basin. Located in the State of Pará, the Belo Monte Dam is the largest, most recent hydroelectric project in the region and third largest in the world. The city of Altamira, 52 kilometers upstream from the dam, served as the main location for construction staging efforts. Altamira experienced rapid population increase that led to greater water and wastewater disposal demand, stressing local sanitation services. The waste disposal practices and sanitation services in Altamira are similarly precarious throughout the Amazon Basin and the developing world. Hydroelectric dams promise to leave as a legacy improved water quality and basic sanitation. Thus, using Belo Monte and Altamira as a model system, the purpose of this research is to examine the social factors and environmental processes that challenge basic sanitation in communities located upstream of major hydroelectric development projects and identify ways in which they impact the welfare of the population. Using social surveys, water sampling, groundwater monitoring, and statistical and spatial analyses, we gathered geographical, social, hydrological, and biological data, to identify high-risk locations with potential fecal contaminant presence in drinking water wells stemming from nearby septic tanks. Further, we examine socioeconomic variables that may explain differential contaminant exposure and ingestion risks.

Considering sanitation both an important societal and environmental issue that affects

water quality, and public health and safety, this dissertation provides a framework that can be used to identify social and environmental vulnerabilities to water well contamination. Identifying the areas and seasons where there are increases in fecal contaminants can aid in the potential reduction of negative impacts to local residents and their groundwater resources that can emerge from large hydropower development projects. The multidisciplinary methods, tools, and analyses presented in our work bring together approaches from the natural and social sciences, serving as a model of convergent research that advances future work across disciplines. The results can become an important reference in guiding the implementation of public health and sanitation efforts in order to minimize social and environmental impacts in communities that will be affected by major development projects not only in Brazil, but across the world.

This dissertation is dedicated to the family, friends, and colleagues who pushed, fueled, helped, and loved me through it all. Thank you for being a part of my growth.

*Pero sobre todo: Para mi mamá.*

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## INTRODUCTION

Ensuring access to affordable, reliable, sustainable, and modern energy for all is one of the main Sustainable Development Goals (SDGs) established by the United Nations (United Nations, 2017). One target of this SDG is to substantially increase renewable energy globally by 2030. As the world's primary renewable energy resource, hydropower plays a leading role in developing countries' sustainable energy portfolios and provides varying levels of energy to 159 countries (International Energy Agency, 2016). With raising questions regarding their negative social and environmental impacts (Moran et al., 2018), the United States of America has removed 1,200 dams over the last two decades - with 82 removals occurring in 2018 alone (O'Connor et al., 2015; Ryan Bellmore et al., 2017). Further, European countries including France, Portugal, Spain, Sweden, Switzerland, and United Kingdom, have removed over 3,900 dams as of 2018 (Gough et al., 2017; Moran et al., 2018). However, these removals are opposite to the recent trend of new large hydropower dams being built in regions with emerging economies, mainly Southeast Asia, South America, and Africa (Chen et al., 2016; O'Connor et al., 2015). In these regions, energy development makes part of the national agenda for economic development with at least 3,700 major dams with a capacity of more than 1 MW either planned or under construction (Chen et al., 2016; Zarfl et al., 2015). Proliferation of dams is most evident in perhaps the most biodiverse and important basins in the world: The Amazon, Congo, and Mekong Basins (Figure 1). There, proposed projects continue to emerge in order to harvest countries' hydroelectric potentials (Winemiller et al., 2016).

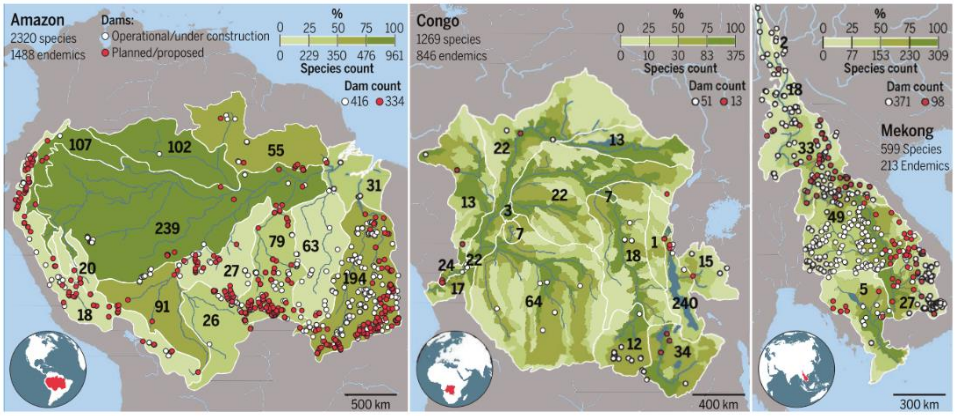


**Figure 1.1:** Proliferation of dams in the Amazon, Congo, and Mekong Basins.
*(Winemiller et al., 2016)*

Second only to China, Brazil remains the fastest growing country in new installed hydropower capacity for both 2016 and 2017 (International Hydropower Association, 2018a, 2017). Brazil has the largest installed hydropower capacity in South America (Table 1.1), comprising two thirds of the continent's total hydropower. more than three-quarters of the nation's total electricity demand is supplied with hydropower, and the Brazilian Amazon Basin holds 42.2 percent of the country's total hydroelectric potential (Ministério de Minas e Energía and Empresa de Pesquisa Energética, 2015; Soito and Freitas, 2011). Government strategies to increase energy security, economic growth, and industrialization are looking towards the Amazon Basin as the future of energy through hydropower with over 100 dams planned in the basin (Luporini and Cruz, 2015; Timpe and Kaplan, 2017; Zarfl et al., 2015).

**NEW INSTALLED CAPACITY BY COUNTRY***

| Rank | Country | Capacity added (MW) |
|---|---|---|
| 1 | China | 8,540 |
| 2 | Brazil | 3,866 |
| 3 | Pakistan | 2,487 |

* including pumped storage

**Table 1.1:** Where has hydropower capacity been added in 2017?
*(International Hydropower Association, 2018b)*

While Brazil looks to hydropower as its main energy source, the negative social and environmental impacts of dams and other large developments in the Amazon Basin have long been pointed out by scholars and questions about hydropower in this globally important watershed continue to be debated (Bingham, 2010; Fearnside, 2014, 2006, 2001; Moran et al., 2018; Moran, 2016, 1981; Smith, 1982; Soito and Freitas, 2011). Countries hosting large hydroelectric projects are oftentimes inspired by the promise of job creation and reduction in fossil fuel dependence yet people displaced and disenfranchised by large hydropower projects can remain impoverished decades later. In Zambia, the Kariba Dam, built in the 1950's, displaced approximately 57,000 whose livelihoods remain affected and rooted in poverty to this day (Scudder, 2016, 2005). In other cases such as the Inga Project in the Congo Basin, and the Tucuruí and Belo Monte Dams in the Amazon Basin, the energy harvested largely bypasses consumers in the host cities and primarily benefits high use consumers such as mining and aluminum smelting companies and distant urban areas (Bosshard, 2015, 2013, Fearnside, 2006, 2001). Nonetheless, in the cities where they are built, large dams continue to be seen as offering the prospect for a brighter future and as a symbol of prosperity (Ansar et al., 2014; Urban et al., 2015). Promised positive outcomes from dam construction include more employment, new hospitals and schools, improved water, health, and sanitation services, and overall regional economic development. On the other hand, poverty seems to increase in the districts where dams are built (Duflo and Pande, 2007; Pottinger and Hathaway, 2008) and locals rarely gain the promised benefits (Moran et al., 2018).

One of the main impacts linked to large developments in the Amazon is the significant and sudden increase in population (Dos Santos Franco et al., 2018; Fearnside, 1999; Moran et al., 2018; Moran, 2016). This is mostly due to large inflows of migrants looking for construction or construction-related employment. Previous dam development projects in the Brazilian Amazon region [e.g. Tucuruí Hydroelectric Dam] have shown up to six-fold increases in population within the immediate areas of construction, reaching double the original population in ten years and severely straining the infrastructure of the area (World Commission on Dams, 2000). The explosive population growth stresses local resources, leaving hospitals, schools, police, and basic sanitation services unable to serve all the incoming population (Grisotti, 2016; Moran, 2016). Unplanned settlements sprout to accommodate the expanding demographic, presenting a challenge to the already limited infrastructure in the Amazon region. This is particularly true of basic sanitation, a regularly observed impact in the Brazilian Amazon region (Tundisi et al., 2003; World Commission on Dams, 2000).

Although access to energy plays a key role in national development agendas, access to clean water and adequate sanitation services remain a concern and are also of paramount importance in the health and well-being of nations. Sanitation remains an issue in many countries, with two billion people worldwide lacking access to these basic services (UNICEF and WHO, 2019). Areas with limited access to clean drinking water and sanitary infrastructure are vulnerable to diseases (Borchardt et al., 2003; Hunt et al., 2010; Verhougstraete et al., 2015; Weiss et al., 2016; World Commission on Dams, 2000), making access to appropriate water and sanitation services a pivotal issue in the protection of human health. Although capital cities often have higher coverage of basic services (UNICEF and WHO, 2019), a lack of water and sanitation infrastructure in smaller cities hosting large hydropower developments can be a reflection of the socioeconomic inequality observed in these places (Cushing et al., 2015).

In the states of the Brazilian Amazon, the provision of sanitation services lag behind the rest of the country with 55.4 percent of residents having potable water from a distribution network and only 10.5 percent receiving sewer services (Ministerio das Cidades, 2018). Under these conditions, and not unlike other dam hosting areas, residents in the region resort to water wells for their water supply and septic tanks for waste disposal (Gauthier and Moran, 2018). These septic tanks generally have an open bottom, allowing liquids to percolate through the soil and reach shallow groundwater resources. The increase in population brought by new hydropower development projects present a challenge to the already limited infrastructure in the Amazon region. Often given the most basic water and sanitation facilities, host communities suddenly face severe pressure on their services and infrastructures stemming from the sudden increase in population. Incoming residents build new wells and septic tanks to provide for their water and waste disposal needs, resulting in greater volumes of septic tank contaminants reaching the same groundwater resources that feeds drinking water wells.

One such city is Altamira, which served as the main location for staging efforts of the Belo Monte Hydroelectric Complex, the largest hydroelectric project in the region and third largest in the world. Located in the state of Pará, Belo Monte brought a sudden population increase to Altamira which led to greater water demand and wastewater disposal, stressed sanitation services, and resulted in contamination of groundwater resources, the main drinking water source in the region. Altamira's disposal practices and sanitation services are not unlike the rest of the cities located in the Brazilian Amazon and the developing world. Thus, using Belo Monte and Altamira as a model system, ***the purpose of this research is to distinguish the social factors and environmental processes that challenge sanitation in communities located upstream of major hydroelectric development projects and identify ways in which their relationship impacts the welfare of the population.*** Combining multidisciplinary approaches, this dissertation investigates the human-nature interactions that affect the sanitation and welfare of communities enduring the challenges arising from hydroelectric expansion, not only in the Amazon, but globally.

Impacts to sanitation from hydroelectric expansion throughout the Amazon Basin remains an insufficiently examined issue. Viewing large hydroelectric development projects as water-energy systems, this study assesses how environmental and social processes interrelate to affect sanitation and the welfare of communities in the context of large hydroelectric development project expansion. Mainly, interactions between human (i.e. social, legal, economic) and natural processes (i.e. geographic, biologic, hydrologic) are observed using integrated multidisciplinary approaches to reveal intricate processes not evident when studied separately by the social or natural sciences.

Through the interdisciplinary study of hydropower as a complex water-energy nexus in the Amazon Basin, the results of this dissertation can aid in the prevention and potential reduction of negative impacts emerging from hydropower development. This work aims to expand international cooperation and support to developing countries in water and sanitation-related activities and investigations. Further, it intends to contribute to literature that addresses ways for ensuring availability and sustainable management of water and sanitation for all, as stated in the United Nations' Sustainable Development Goals (SDGs). This dissertation directly addresses the main targets of this SDG, which include, 1) equitable access to safe and affordable drinking water by increasing the portion of population using safely managed water services, and 2) adequate and equitable access to sanitation by increasing the population using safely managed sanitation services. Considering sanitation both an important societal and environmental issue that affects water quality, and public health and safety, we explore the connections between contaminant transport, spatial distribution and geography, and socioeconomic level to potentially avoid future sanitation collapses in cities affected by major hydroelectric development projects.

## 1.1 Study Area

The Belo Monte Hydroelectric Complex was born out Brazil's goal to secure a reliable power supply. As the largest project in the Amazon region and third largest worldwide, it has the potential to generate an average of 11 gigawatts per hour of operation serving an estimated 60 million people across 17 Brazilian states. Located along the Xingú River in the State of Pará, the city of Altamira lies 52 kilometers upstream from Belo Monte and served as the main staging area for construction efforts. Belo Monte's construction began in 2011 with inauguration of the 14th turbine occurring in 2019 (Globo G1 Pará, 2019), and brought more than 30,000 construction and service sector workers to urban Altamira. Population rose from 77,439 inhabitants in 2010 to an estimated 109,938 in 2016 (Instituto Brasileiro de Geografia e Estatística, 2011a; Instituto Brasileiro de Geografia e Estatitica, 2016). Nonetheless, people in the area estimate the population may have been closer to 150,000 inhabitants at the peak of its construction in 2012, settling back to 110,000 by 2016 (Marin and Oliveira, 2016; Moran, 2016). As previously discussed, the population increase brought forth by Belo Monte's construction stressed the city's water distribution and sanitation services, particularly through greater water demand, wastewater disposal, and solid waste generation (Gauthier et al., 2019). While national legal frameworks for water quality and sanitation existed long before Belo Monte's construction, these were unable to mitigate the impact the project had on local sanitation services and, subsequently, adequate drinking water sources.

The dam's reservoir flooded parts of the city leading to relocation of families which, along with the population increase, augmented population density and restructured the city's layout. Unplanned settlements also sprouted to accommodate the expanding population, presenting a challenge to Altamira's water distribution network which could not keep up with the demand. Aside from the historical dependency on water wells in Altamira, the unreliability of the water distribution system reinforced the use of shallow-dug wells as a source of drinking water in the city (Gauthier et al., 2019; Gauthier and Moran, 2018; Pessoa, 2016; Promotoria da Justiça do

Ministério Público, 2018). At the same time, and since its establishment in 1880, Altamira never had a wastewater collection network and residents discharged sewage in open air ditches, septic tanks, or surface waters (Norte Energia, 2011; Norte Energia S.A., 2011; Promotoria da Justiça do Ministério Público, 2018). Not unlike many Amazonian cities, open bottom septic tanks are the main wastewater disposal system in the urban area (Brondizio, 2016; Gauthier et al., 2019; Gauthier and Moran, 2018; Pessoa, 2016; Procuradoria da República no Pará, 2016). These septic tanks have an open bottom, allowing liquids to percolate through the soil.

In cities experiencing sudden population growth, high septic system densities and their association to endemic illnesses (Borchardt et al., 2003; Hunt et al., 2010) are cause for great concern. As population density increases, new wells and septic tanks are built and distances between structures decrease, reducing transport times from septic tanks to water wells. Feeding off a single unconfined aquifer (CPRM Serviço Hidrogeológico do Brasil, 2014), the increases in septic discharges to the ground in the city of Altamira can lead to contaminants leaching to the water below, ultimately reaching wells and putting the health of the population at risk of contaminant ingestion. (Gauthier et al., 2019; Ministerio Publico Federal, 2016; Pessoa, 2016; Risebro et al., 2012; Verhougstraete et al., 2015). The provision of sanitation services and disposal practices witnessed in Altamira are similar along the Amazon region and developing world. As dams continue to play significant roles in energy production, the need to minimize environmental, social, and health issues arising from hydroelectric expansion becomes crucial. In this sense, Belo Monte and Altamira can serve as a model system for the study of multidisciplinary factors affecting basic sanitation and quality of life in communities affected by major hydroelectric projects, to avoid similar issues from emerging in future endeavors.

## 1.2 Research Objectives

Objective 1 - Determine the environmental processes affecting sanitation, particularly drinking water and wastewater by:

a. Assessing contaminant transport from septic tanks to wells by monitoring groundwater levels and analyzing samples from drinking water wells in both seasons.
b. Analyzing if the processes affecting contaminant transport are dependent on groundwater depth and population density.
c. Examining if contaminant transport from septic tanks to water wells has a temporal component, showing changes between seasons.

Objective 2 - Determine the social factors affecting sanitation by:

a. Reviewing national policies and analyzing their implementation based on the sanitation and water services provided to the population.
b. Procuring sanitation services received and practices at the household level (e.g. water use, treatment, and disposal, solid waste management) to address relationships between these variables and the socioeconomic level of the population.
c. Observing socioeconomic level as a determining factor in the access to water, water quality, use of water treatment alternatives, and connection to city services.

Objective 3 – Identify populations at risk of exposure or ingestion of contaminants by:

a. Examining relationships between socioeconomic levels of the population and presence of contaminants in drinking water wells.
b. Assessing associations between socioeconomic level and the prevention of contaminant ingestion through water treatment alternatives, treated water purchase, or connection to water distribution services.

c. Providing a more conclusive determination of the populations at risk based on relationships between groundwater depth, population density, contaminant presence and concentration, and socioeconomic level.

## 1.3 Dissertation Outline

Objectives are addressed by integrating geographical, social, hydrological, and biological data and methods to examine the socioeconomic and environmental variables that impact sanitation and explain the exposure of drinking water wells to contaminants as well as the prevention of contaminant ingestion in households in order to better assess populations at risk.

In the second chapter of this dissertation, we present the first study, which utilizes spatial analytical data and terrain analyses to identify high-risk locations within the densest populated neighborhoods in Altamira. It develops a heuristic for identifying areas susceptible to groundwater and drinking water well contamination based on elevation, groundwater levels, and well and septic tank distances to rainfall induced flow paths and flow accumulation areas.

With the goal of constructing a more comprehensive understanding of sanitation in Altamira, the third chapter of this dissertation presents a second study, which applies surveys and structured interviews to identify Altamira's sanitation practices, services provided, and hindrances in adequate service provision after the construction of Belo Monte. Reviewing national water and sanitation policies, discrepancies between Altamira's current circumstances and gaps in policy implementation are discussed.

Building on these results, the fourth chapter of this dissertation encompasses a third study which assesses contaminant transport to drinking water wells through seasonal groundwater monitoring and fecal contaminant sampling in 30 households previously identified within low- and high-risk areas of Altamira. Relationships between concentration and presence of contaminants, their seasonal differences, depth to water table, and population density are observed. The spatial and temporal understanding of contaminant presence provided in the third study, allowed for the exploration of socioeconomic level and its importance in the exposure and ingestion of these contaminants in last study and fifth dissertation chapter. Using statistical analyses, the last study in this dissertation employs visual observations, survey data, and contaminant results from the previous sample to study the relationships between socioeconomic level, presence and concentration of contaminants in drinking water wells, sanitation services received, and sanitation practices in households. The sixth chapter of this dissertation concludes lessons learned from Belo Monte and Altamira, addressing ways in which improved water and sanitation services can take place in the context of hydropower projects. This last chapter ultimately unravels the importance of using both social and environmental components to further understand the relationship between human - environment interactions and their place in the development of large hydroelectric projects elsewhere.

## HYDROELECTRIC INFRASTRUCTURE AND POTENTIAL GROUNDWATER CONTAMINATION IN THE BRAZILIAN AMAZON: ALTAMIRA AND THE BELO MONTE DAM[1]

### 2.1 Abstract

Heavy investments in hydroelectric development are occurring throughout the Amazon Basin, holding 42.2 percent of Brazil's hydroelectric potential. The Belo Monte dam is the most recent and largest project in this region. The prevalence of septic systems in the Amazon, coupled with the widespread use of water wells and rising water table from filling the reservoir, create sanitation and health concerns for upstream communities. Using spatial analytical data and terrain analyses, we identify high-risk locations within the most densely populated neighborhoods in Altamira, Belo Monte's host city. The purpose of this research is to develop a heuristic for identifying areas susceptible to groundwater and well contamination in relation to existing and proposed hydroelectric projects. Altamira's city center persists as a high-risk location for contamination of wells because of its population density and relatively low elevation compared to other parts of the city. The methods, tools, and analyses presented in this paper provide a framework that can be used to identify vulnerability to groundwater and drinking well contamination. The results presented here can guide implementation of public health and sanitation efforts in areas impacted by large hydroelectric projects to avoid future water quality crises.

[1] This is an Accepted Manuscript of an article published by Taylor & Francis in *The Professional Geographer* on 15 January 2019, available online at doi.org/10.1080/00330124.2018.1518721. Reference: Gauthier, C., Zihan, L., Peter, B., Moran, E.F. 2019. *Hydroelectric Infrastructure and Potential Groundwater Contamination in the Brazilian Amazon: Altamira and the Belo Monte Dam.* The Professional Geographer. 71(2): 292 - 300.

## 2.2 Introduction

Between 1973 and 2014, worldwide hydroelectric production increased by 207 percent (International Energy Agency 2016). Although hydroelectric power provides energy to a total of 159 countries, China, Canada, and Brazil account for 45.7 percent of the global hydroelectricity production (International Energy Agency 2016). Canada and Brazil's national grids depend on hydropower for 58.3 percent and 63.2 percent of their energy demand, respectively (International Energy Agency 2016). While the total installed hydropower capacity per year has been increasing since the 1970s, the number of dams completed worldwide per year has been decreasing (Chen et al. 2016). This is an indication that dams have been designed and built with greater hydropower capacity. A growing number of countries in Europe and North America remove many dams each year, with approximately 800 dams removed in the U.S. alone from 1999 to 2016 (American Rivers 2016). However, in regions with lower levels of socio-economic development, hydropower capacity has been increasing over the past six decades (Chen et al. 2016). In the Amazon, Congo, and Mekong Basins, for example, proliferation of dams is evident, and proposed projects continue to emerge, harvesting the countries' hydroelectric potential (Winemiller et al., 2016).

Hydroelectric power is the primary energy source in Brazil, accounting for 65.2 percent of the total domestic electricity generated (Empresa de Pesquisa Energética 2014; Ministerio de Minas e Energia 2015). Given that the Amazon Basin holds 42.2 percent of Brazil's hydroelectric potential (Ministerio de Minas e Energia 2015), it comes as no surprise that the Brazilian Development Bank has invested in significant long-term loans for hydroelectric development in this region (e.g., Santo Antonio—$1.7 billion USD, Jiraú—$2.7 billion USD, and Belo Monte—$6.3 billion USD) (Luporini andCruz 2015). The latter, Belo Monte, is the most recent and largest hydroelectric project investment in the region to date.

This paper focuses on potential groundwater contamination resulting from flooding of areas upstream of complexes such as Belo Monte. The prevalence of septic systems in the region, coupled with the widespread use of water wells and rising water tables, can create sanitation and health concerns for populations in these areas. The purpose of this research is to develop a heuristic to identify areas susceptible to groundwater and drinking well contamination that could result from hydroelectric infrastructure development. Using a suite of spatial analytical data, methods, and terrain analyses, we identify high-risk locations within the most densely populated neighborhoods in Altamira, Belo Monte's host city. This is achieved by pairing hydrologic modeling with monitored groundwater measurements. Identifying contamination risks associated with water resources affords an opportunity to anticipate problems that may emerge, or already exist, as a result of large hydroelectric dam construction. The framework presented here can equip researchers and local governments with necessary information to address the basic sanitation and public health needs of residents surrounding these hydroelectric complexes. Our framework consists of: (1) locating and describing residential wells and septic tanks in the city of Altamira, (2) locating monitoring wells and collecting groundwater measurements in the area, (3) interpolating groundwater elevations throughout Altamira, (4) estimating surface water flow and accumulation areas, and (5) assessing risk of wells using groundwater depth and proximity to surface flow paths.

### *2.2.1 The Belo Monte Hydroelectric Complex*

Located in the State of Pará in the Brazilian Amazon Basin, the Belo Monte Hydroelectric Complex is the third largest in the world. It is comprised of 24 turbines and 28 dikes, creating a reservoir with a surface area of 478 $km^2$ along the Xingú River (Diniz de Figueiredo 2015). The project dates back to 1975, when the Hydroelectric Inventory Study of the Xingú River revealed the region's energy generation potential. The Xingú Watershed is the second largest of all watersheds located on the south margin of the Amazon River, both in size and hydroelectric potential (Agência Nacional de Águas 2013). This makes the area a prime location for the development of hydroelectric complexes. In the 45 years since its initial proposal, Belo Monte was fiercely opposed and marked by a series of controversies, conflicts, protests, and an "intricate legal battle that unraveled opposing laws, direct and preliminary actions, and the involvement of the Supreme Federal Court, Public Prosecutor's Office, Regional Courts, and civil society organizations such as the Socio-Environmental Institute, Greenpeace, and the Coordination for the Indigenous Organizations of the Brazilian Amazon" (Cândido Fleury and Almeida 2013: 145).

Despite being surrounded by licensing drawbacks, civil protests, and judicial disputes, Belo Monte received its construction license in 2011 and began running its first turbine in February 2016, with plans to run all 24 turbines by 2019 (Empresa Brasil de Comunicação 2016). Diverting 80 percent of the Xingú River's flow towards the turbines, the complex has the potential to generate an average of 11,233 megawatts per hour of operation, which will be distributed to 17 Brazilian states, serving approximately 18 million residences (an estimated 60 million people in total). Belo Monte's construction was projected to include controlled flooding in areas upstream of the dam. This flooding included portions of urban Altamira (Norte Energia 2011), which caused the eviction and resettlement of residents living below an elevation of 100 meters above sea level.

### *2.2.2 The City of Altamira*

Located 52 kilometers upstream from the dam, the city of Altamira served as the main stage for the construction of Belo Monte (Figure 2.1). Since construction of the dam, Altamira's population grew from 77,439 inhabitants in 2000 to an estimated 109,938 in 2016, as more than 30,000 dam workers and migrants temporarily settled in the area (Instituto Brasileiro de Geografia e Estatística

2011; Instituto Brasileiro de Geografia e Estatitica 2016). Altamira's urban area now covers 112.9 square kilometers and contains 19 neighborhoods (Instituto Brasileiro de Geografia e Estatitica 2016). The city's controlled flooding of the urban area led to the creation of five collective urban resettlements built to relocate affected families from low-lying areas. These relocations, along with the population increase, augmented population density in certain neighborhoods and restructured the city's layout (Instituto Brasileiro de Geografia e Estatitica 2016). Flooding of some urban areas as a result of Belo Monte construction also created changes in groundwater levels, bringing the city's water table closer to the surface.

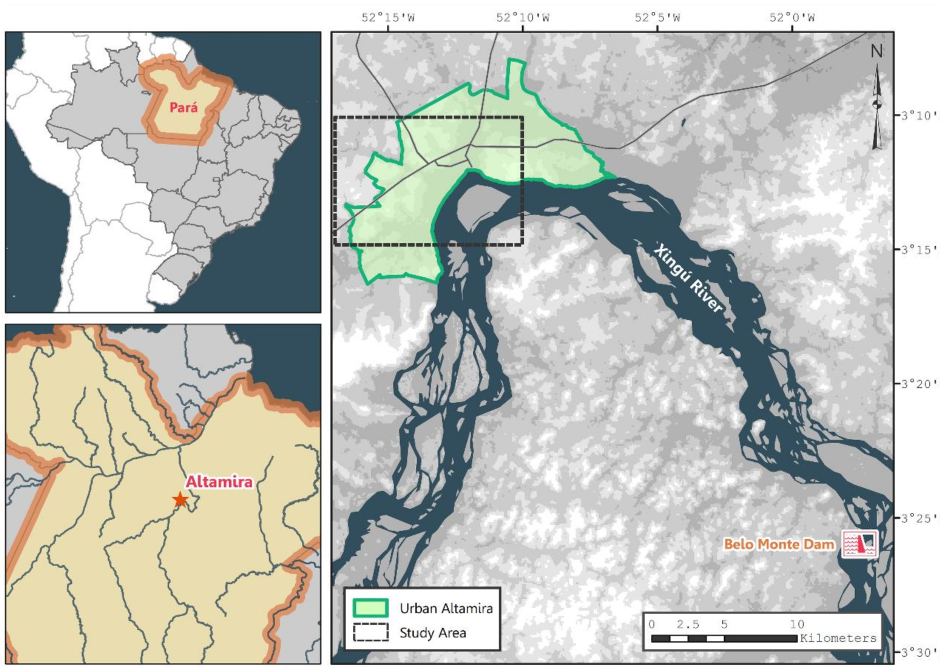


**Figure 2.1:** Altamira, located along the Xingu River in the Brazilian Amazon Basin, Pará

Moreover, the population increase brought forth by the Belo Monte Hydroelectric Dam construction has stressed the city's basic sanitation services, particularly through greater water demand, wastewater disposal, and solid waste generation. Irregular water service delivery or no connection to the local water distribution system has led to an increase in shallow-dug wells. At the same time, septic tanks remain the main wastewater disposal system throughout the city

(Pessoa 2016). Septic tanks in Altamira generally have an open bottom, allowing liquids to easily percolate through the soil. Septic tank discharges to the ground coupled with shallow wells and an increase in water pumping due to greater water demand can lead to septic tank contaminants reaching water wells, putting the health of the population at risk (Ministerio Publico Federal 2016). This problem was deemed critical by Brazil's Federal Public Ministry and in April of 2017, Belo Monte's license to operate was suspended until the sanitation crisis is fully addressed (Ministerio Publico Federal, 2017, 2016; Pessoa, 2016).

### *2.2.3 Emergent Groundwater Contamination*

Drinking water wells are vulnerable to contaminants that travel along fast groundwater flow paths; even a small amount of virus-laden water from a septic tank can constitute a significant health risk at the well head (Hunt et al. 2010). Viruses are thought to lose their infectivity after one to two years in the subsurface (De Roda Husman et al. 2009; John andRose 2005), but high capacity pumping results in sufficiently short travel times for the transport of infectious viruses to the drinking wells. Although groundwater travel times are commonly longer than one year in unstressed systems, they can be much shorter near high-capacity pumping wells (Hunt et al., 2010). Given that high septic system densities have been associated with endemic diarrheal illnesses (Borchardt et al. 2003), and that the growing population is heavily dependent on water wells (also increasing pumping), short transport times from septic tanks to wells are a growing concern in Altamira and other locations with similar terrain and infrastructure (Borchardt et al. 2003; Hunt et al. 2010). Furthermore, rainfall induced infiltration can threaten drinking water supplies. In Altamira's wet season, intense rains flood parts of the city, along with low-laying well heads. Problematically, flooding of areas upstream of large hydroelectric projects is inevitable, and Belo Monte has expanded the areas that commonly flood within Altamira, increasing contaminant infiltration to wells located nearby.

### *2.2.4 Surveyed Households and Monitoring Well Data*

One hundred and thirty household surveys were conducted in the urban area of Altamira in July of 2016. The distribution of the questionnaires was determined by the "Probability Proportional to Size" method (Kalton 1983; Groves 2009; Randell and VanWey 2014), where the probability of selecting an element is directly proportional to its size. Data on individual neighborhood and total urban populations were gathered from the IBGE to determine population density per neighborhood (IBGE, 2015). Specifically, if one neighborhood is more densely populated than another, it will have a greater chance of being sampled. The 13 most densely populated neighborhoods (out of 19) in urban Altamira were sampled, with surveys distributed across elevation gradients. Septic tanks and neighboring water wells are typically separated by greater distances in low population density neighborhoods; hence, the remaining 6 neighborhoods with a lower population density were excluded from this study. The survey instruments collected data on drinking water well locations, wastewater tank locations and volumes, water-use and wastewater management, including water services received, household water-use, water well depth, and septic tank dimensions.

Semi-structured interviews were performed in June and July of 2016 with personnel from the following local offices and government branches: Brazilian Institute of Geography and Statistics (IBGE), Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), Secretariat of the Environment (SEMAT), Public Sanitation Department (DLP), Sanitation Company (COSALT), and Secretary of Urban Planning (SEPLAN). Questions related to the current basic sanitation services provided by the city and hindrances in their provision were addressed (e.g. lack of sewer connections, improper potable water booster pump design, and energy shortages in water treatment plants). Publicly available groundwater monitoring reports were collected from an IBAMA (IBAMA 2016) online repository. Quarterly measurements from 56 monitoring wells in the region were gathered for the years between 2012 and 2015. Of these, 40 monitoring wells were located within the urban area of Altamira.

### 2.3 Methods

The heuristic presented here identifies areas where drinking water wells may be vulnerable to contaminants from septic tanks through a deterministic risk assessment that considers the vertical relationship between surface elevation and groundwater elevation, as well as proximity to projected areas of concentrated water flow and accumulation. The general framework consists of (1) deriving flow paths and flow accumulation areas from the digital elevation model (ASTER GDEM V3) (NASA LP DAAC 2001), (2) calculating groundwater elevations at the monitoring wells using the digital elevation model and recorded groundwater depths, and (3) interpolating a continuous surface of groundwater depths across Altamira.

During the wet season, intense rains flood parts of the city, along with low-laying well heads. Projected flow direction and flow accumulation were used to determine contaminant accumulation areas and flow paths of contaminants released from overflowing septic tanks during the intense rain events common to the Amazon region. These flow paths and accumulation areas are heavily affected by rainfall induced infiltration, resulting in contaminant transport from septic tanks to wells. Similarly, septic tanks are susceptible to water intrusion from, or seepage to, nearby water flows. During the wet season, this can further threaten water resource quality in the area and increases the risk of contamination.

Wells located near surface flow paths and projected flow accumulation areas are more vulnerable to contaminant intrusion during the rainy season, when flooding is common in parts of the city. A 30-meter resolution Advanced Spaceborne Thermal Emission and Reflection

Radiometer Global DEM (ASTER GDEM V3) (NASA LP DAAC 2001), obtained from the NASA Reverb|Echo repository (EOSDIS 2009), was used to calculate flow direction over the urban area. First, using ArcGIS Spatial Analyst Hydrology tools, we filled "sinks" in our surface elevation raster so that water flow would proceed (ESRI 2013). The depressionless DEM was the input for the flow direction process, which determines the path of water travel from each cell. The flow direction output was used to determine flow accumulation. This yielded the most probable flow paths and accumulation areas for surface water.

ESRI's ArcGIS suite was used to map septic tanks and household water wells (ESRI 2015). Using data from the 40 groundwater monitoring wells located in the urban area of Altamira, the highest (i.e., nearest-to-surface) recorded measurements of water level for each monitoring well were identified. These measurements correspond to the shallowest groundwater levels observed in each monitoring well, from the ground surface to the unconfined aquifer below. These measurements were recorded during the Brazilian Amazon's rainy season. Given that wells in areas with shallower groundwater depths are more vulnerable to contaminant intrusion from nearby septic tanks, these shallow levels were considered the most crucial for our determination of risk.

To estimate groundwater levels throughout Altamira, we performed ordinary kriging on groundwater elevations at the 40 monitoring wells located in urban Altamira using the shallowest measurements available (i.e., groundwater levels nearest the surface). Groundwater elevations were calculated by taking the difference between recorded groundwater depth and surface elevations provided by the ASTER digital elevation model (ASTER GDEM V3) (NASA LP DAAC 2001). Control points were used to demarcate surface water bodies such as the Xingú River and the four streams within the city that drain to it. We then subtracted the interpolated groundwater elevations from the digital elevation model to estimate groundwater depth at each pixel. Determination of risk was assessed by reclassifying groundwater depths into seven equal interval categories. Household wells located in shallow groundwater levels within the city are considered to be most at risk for quicker travel times of potential septic tank contaminants in groundwater and from surface runoff. Furthermore, the United States Environmental Protection Agency (EPA) guidelines dictate that drinking household wells should be a minimum of 76 meters away from streams and flooded areas in order to minimize contamination (Environmental Protection Agency 2002a; Environmental Protection Agency 2002b). Households wells along this 76-meter buffer are determined to be most at risk for potential septic tank contaminant intrusion to nearby wells or surface water bodies. Hence, additional risk assessment of potential well contamination from surface water flow was performed by creating buffers of 76 meters to streams and flooded areas. Flooded areas were predicted at 100 meters above sea level by dam developers and Altamira's urban planning office. The 76-meter distance to streams and flooded areas can also serve as a buffer in further assessing potential septic tank water intrusion from, or seepage to, nearby water flows which can further threaten water quality in the area.

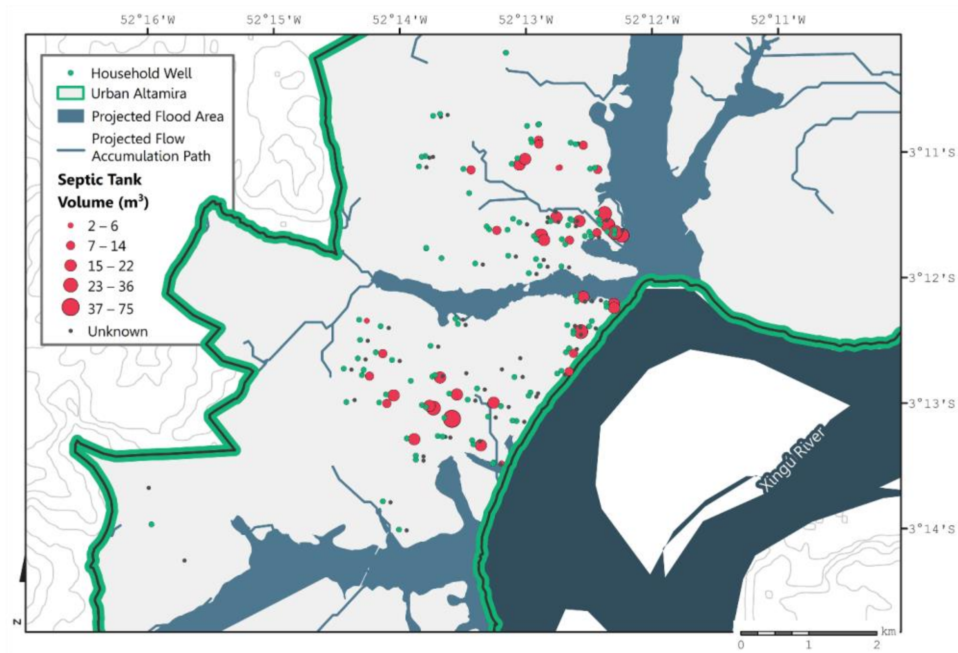


**Figure 2.2:** Location of surveyed household wells, septic tanks, projected flow accumulation paths, and projected flood areas in urban Altamira.

*Projected flood area source: SEMAT (2016).*

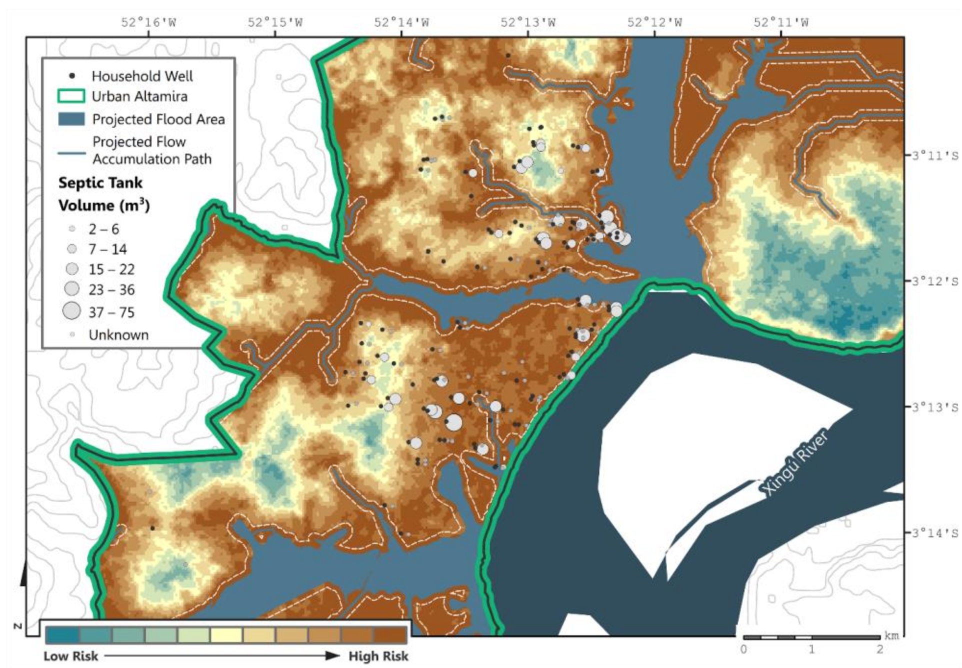


**Figure 2.3:** Interpolated groundwater depths (based on nearest-to-surface wet season groundwater measurements from monitoring wells), control-flooded area, and projected flow accumulation.

*Projected flood area source: SEMAT (2016).*

## 2.4 Results and Discussion

Except for the five collective urban resettlements recently built for displaced individuals, every household in Altamira has a septic tank. Theoretically, septic tanks with higher volumes will leach more fluids to the ground. Hence, septic tanks with higher volume pose a greater risk of contamination to nearby wells. Dot density was used to show varying septic tank volumes within our surveyed data (Figure 2.2). Well locations and septic tanks of the households surveyed are shown in relation to projected flow accumulation streams and control-flooded areas created by the dam (Figure 2.2). Results from our projected flow accumulation analysis show flow paths draining to the control-flooded portions of urban Altamira, ultimately leading to the Xingú River. In the case of heavy rain events, septic tanks can overflow and allow contaminant entry to wells through surface infiltration. For this reason, wells closest to projected flow accumulation paths are more at risk of pollutant entry from surface flow contaminants carrying septic tank overflow.

Results from the interpolated nearest-to-surface groundwater measurements for the city of Altamira, along with surveyed wells and septic tanks, are shown in Figure 2.3. A shorter distance from the water table to the ground surface represents a higher risk of contaminant entry from septic tanks and cross contamination to water wells. Shallower water table depths are observed throughout urban Altamira but are most prevalent in the eastern, southwestern, and central portions of the city. The urban center of Altamira, located along the banks of the Xingú River, is a densely populated area. Its high population density, coupled with shallower water table depths, makes the location a particularly high-risk area for pollutant intrusion from septic tanks and cross contamination of wells.

Wells located in areas within 76 meters of flow paths are at higher risk of suffering pollutant entry from surface flow infiltration. Figure 2.3 shows that, of the wells surveyed, those that intersected these buffers are at higher risk of suffering infiltration of surface flow from overflowing septic tanks during high rain events. Similarly, septic tanks located within 76 meters from control-flooded areas, located at an elevation of 100 meters above sea level, can seep pollutants to neighboring water bodies, increasing the risk of water resource contamination in the region. The majority of the wells located in areas bordering the control-flooded portions of urban Altamira are at risk, with less risk observed in the flooded region northeast.

As the figures show, there are varying levels of contamination risk throughout Altamira. However, wells located in areas with shallower ground-to-water table depths, and in areas within 76 meters of a flow path or a control-flooded area are of particular importance. Under these tenets, the city center persists as a high-risk location for contamination of drinking water wells. This area is of specific importance because of its population density and relatively low elevation compared to other parts of the city, and is often flooded during heavy rain events. An increased probability of infiltration of septic tank pollutants to the water table is observed in this area, along with the southwestern portion of urban Altamira, which puts the general groundwater quality of the city at risk.

Future studies could factor the elevation of septic tanks in relation to water wells to further explore contaminant transport between these systems. However, due to the population boom that occurred in Altamira after the decadal census, there is a data gap in the location and number of septic tanks and water wells throughout the city. Hence, mapping of current septic systems and water wells throughout the entirety of the city was not possible in this study. The absence of official information, and the government's lack of resources to conduct a mid-term census, prevents from having an adequate inventory of drinking wells and septic tanks and leaves agencies providing basic sanitation services in the dark. Similarly, the lack of monitoring wells in the westernmost and easternmost portions of urban Altamira, create a data gap that hinders precise estimates of the groundwater levels in these areas. Current population estimates for Altamira are based on national calculations that do not consider population booms brought forth by large scale development projects such as Belo Monte. Nonetheless, even in data deficient study areas, identification of contamination risks in water resources is feasible and can aid in anticipating potential public health and sanitation issues that may emerge as a result of large hydroelectric projects.

### 2.5 Conclusions

The vast majority of the urban and rural populations in the Brazilian Amazon are not served by any sewage collection or treatment (Brondizio 2016). As more dams in the Amazonian region are planned, groundwater contamination issues like those found in Altamira are an expected recurring challenge. The population booms brought forth by dam projects in combination with proliferating septic tank and water well use can pose human health risks to communities where dam construction is proposed. The methods, tools, and analyses presented in this paper provide a replicable framework that can be used to identify vulnerability of groundwater and drinking well contamination in areas upstream of hydroelectric developments. These analyses can guide implementation of public health and sanitation efforts in areas impacted by large hydroelectric projects such as Belo Monte to avoid and manage future water quality crises.[2]

[2] Partial funding was provided by Michigan State University's Center for Latin American and Caribbean Studies, and the Department of Geography, Environment, and Spatial Sciences. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (DGE1424871). Any opinions, findings, and conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or that of the other funding sources cited above. Funding agencies had no involvement in the study design; collection, analysis and interpretation of data; in the writing of the report; nor in the decision to submit the article for publication. The authors thank the participants surveyed and officials interviewed. Particularly, Vagner Nascimento, Gustavo Guerzoni, and Fernando Serra. Thanks also to the University of Pará faculty Miquéias Calvi and Alan Araújo, and Michigan State University Faculty Dr. Ashton Shortridge and Dr. David Hyndman for providing comments.

## PUBLIC POLICY IMPLEMENTATION AND BASIC SANITATION ISSUES ASSOCIATED WITH HYDROELECTRIC PROJECTS IN THE BRAZILIAN AMAZON: ALTAMIRA AND THE BELO MONTE DAM.[3]

### 3.1 Abstract

Located in the State of Pará, along the Xingú River, the Belo Monte Hydroelectric Complex is the largest, most recent project in the Amazon region and third largest in the world. The city of Altamira, located 52 km upstream from the Belo Monte dam, served as the main stage for its construction. Using surveys and interviews performed in 2016 as social and quantifiable tools, we determine basic sanitation practices in Altamira after the construction of Belo Monte and reveal issues that can impact the environment and public health of the population. Through analysis of national policies and the use of publicly available information, we identify discrepancies between Altamira's current reality and Brazil's existing national public policies, mainly Brazil's Water Resources Policy and the Federal Sanitation Law. Similar basic sanitation provision and waste disposal practices along the region lead us to believe that, if not addressed, the implementation gaps observed in Altamira are likely to emerge in future hydroelectric development projects currently envisioned throughout the Amazon Basin. As more dams in the Amazonian region are planned, identifying public policy implementation gaps that affect basic sanitation and water resources creates opportunities to anticipate problems that could impinge on the public health needs of residents where such large infrastructure projects will be implemented.

### 3.2 Introduction

Energy independence and reduction of emissions are objectives often pursued by many nations. In the global south, hydropower development has been touted as a strategy promising to provide these

[3] This is an Accepted Manuscript of an article published by Elsevier in *Geoforum* on 12 October 2018, available online at doi.org/10.1016/j.geoforum.2018.10.001. Reference: Gauthier, C., Moran, E.F. 2018. *Public policy implementation and basic sanitation issues associated with hydroelectric projects in the Brazilian Amazon: Altamira and the Belo Monte Dam.* Geoforum. 97(2018):10–21.

goals. Although a growing number of countries are removing a large number of dams each year, hydropower still provides some level of energy to a total of 159 countries (International Energy Agency, 2016). In regions with lower levels of socio-economic development, hydropower capacity has been increasing rapidly in the past six decades(Chen et al., 2016). Proliferation of dams is evident in the Amazon, Congo, and Mekong Basins, where proposed projects continue to emerge in order to harvest countries' hydroelectric potentials (Winemiller et al., 2016). In the Brazilian Amazon, which holds 42.2 percent of Brazil's hydroelectric potential (Ministério de Minas e Energia, 2015), hydroelectric projects are not new. Located in the State of Pará, along the Xingú River, the Belo Monte Hydroelectric Complex is the largest, most recent project in the Amazon region and third largest in the world.

The city of Altamira, located 52 kilometers upstream from the Belo Monte dam, served as the main location for construction staging efforts. The population increase brought forth by the construction of the dam stressed the city's basic sanitation services through greater water demand, wastewater disposal, and solid waste generation. Belo Monte's environmental licensing required that dam developers provide a significant improvement on such services in Altamira, in part to meet the demands of the growing population stemming from the construction of the dam. Lack of compliance with this requirement created a mounting sanitation crisis. In 2016, Brazil's Federal Public Ministry deemed Altamira's risk of a sanitary collapse a critical issue that had been unresolved in the five years encompassing the construction of the dam (Ministerio Publico Federal, 2016; Conselho da Justiça Federal, 2017) and that remained unresolved.

Altamira's current situation does not coincide with the requirements established by national policies, mainly Brazil's Water Resources Policy and the Federal Sanitation Law. These policies were created to guide water management and basic sanitation in the country. They seek to ensure water quality, sustainable development, and social inclusion, while attempting to minimize environmental impacts related to the implementation and development of sanitation services. Using surveys and interviews performed in 2016 as social and quantifiable tools, we reveal sanitation practices in Altamira after the construction of Belo Monte. Through the use of publicly available information and analysis of Brazil's Water Resources Policy and the Federal Sanitation Law, we identify that Altamira's current practices do not comply with national public policies and we reveal issues that can impact the environment and public health of the population.

The goal of this paper is to reflect on the reasons for the failure in compliance with water and sanitation requirements of the law, and to reveal implementation gaps that have occurred in Altamira and that can continue to emerge in future hydroelectric development projects envisioned throughout the Amazon Basin and the developing world. Looking at the intersection between social, political, and environmental elements, we identify factors that hinder the provision of better water and sanitation services. We hope to provide insights regarding the implications of policy non-compliance on the basic sanitation and quality of life of communities located upstream of large hydroelectric projects in order to ensure population health and protection of the environment.

#### *3.2.1 Belo Monte*

The Xingú River Basin is the second largest watershed located on the southern banks of the Amazon River, both in area and hydroelectric potential (Agência Nacional de Águas, 2013) making it a prime location for hydroelectric project development. In 1975, a Hydroelectric Inventory Study of the Xingú River revealed the region's energy generation potential and thus, plans for the Belo Monte Hydroelectric Complex were first envisioned. The stated goals of the Belo Monte dam were to meet the energy demands of a rapidly growing nation.

Belo Monte's history is long and complicated (Boanada, 2015, 2016; Bratman, 2014;

Jaichand et al, 2013; Hall et al., 2012; Fearnside, 2006;). This section does not attempt to encompass all the intricacies of its conception, design, construction, and operation, but rather present a brief narrative of its progression to date. In the forty five years following its initial proposal, Belo Monte was marked by licensing disputes, civil protests, and judiciary interventions, including "the involvement of the Supreme Federal Court, Public Prosecutor's Office, Regional Courts, and civil society organizations such as the Socio-environmental Institute, Greenpeace, and the Coordination for the Indigenous Organizations of the Brazilian Amazon" (Cândido Fleury et al., 2013). Ultimately, Belo Monte began its construction in 2010.

Diverting 80% of the Xingú River's flow, the project is comprised of 24 power generating turbines and 28 reservoir dikes, flooding a total of 478 $km^2$ of land (Diniz de Figueiredo, 2015). The complex has the potential to generate an average of 11,233 megawatts per hour during rainy season peaks, and an overall annual average of 4,500 megawatts (Empresa de Pesquisa Energética, 2015). This energy will be distributed to 17 Brazilian states serving approximately 18 million residences and 60 million people. Belo Monte began running its first turbine in February 2016, with plans to run all 24 turbines by 2019 (Empresa Brasil de Comunicação, 2016).

In the Brazilian Amazon Basin, over 100 dams are planned (Winemiller et al, 2016; Zarfl et al, 2015) as part of government strategies geared to increase energy security, economic growth, and industrialization (Timpe, 2017). Although Brazil has recently announced a halt on mega-dam development in the region, experts warn that threats remain (Branford, 2018). Viability studies have been accepted for the Jatobá dam on the Tapajós River (CanalEnergia, 2018) and Brazil's National Energy Plan for 2026 lists plans to complete energy transmission lines through the region for the Sao Luiz de Tapajós dam (Empresa de Pesquisa Energetica, 2017). Impacts of these big development projects in the Amazon region have long been studied, however, questions about the impacts of current and future hydropower in this globally important watershed continue to be debated (Moran, 2016, 1981; Soito et al, 2011; Bingham, 2010; Fearnside, 2001; Smith, 1982). In cities such as Altamira, the abrupt population increase brought forth by large development projects such as Belo Monte, has played a significant role in the city's water and sanitation services.

### *3.2.2 Altamira*

Altamira was once a small settlement that acted as a trading post during the rubber boom (1850-1920). Not unlike other towns in the Amazon region, Altamira's population grew considerably during the Trans-Amazon Highway construction which took place from 1971 to 1974. This gargantuan effort at road-building, directed settlement, and geopolitical integration of the Amazon into national development goals was part of the Program of National Integration, announced in 1970 (Moran 1975, 1981, 2016; Smith, 1982). Towns such as Altamira, Marabá and Itaituba began to swell as the construction of the Trans-Amazon and Cuiaba-Santarem Highways opened the region to outsiders. After the first year of highway construction, Altamira's population exploded from approximately 1,000 residents to over 10,000 (Moran 1975). The large influx of people surpassed the capacity of public services to meet demand. By 1972, Altamira's hospital could not keep up with the explosion in road trauma and malaria cases, and schools could not accommodate the student increase (Moran, 1975). Altamira's urban area stabilized in size and commercial activity until 2010, (Moran, 2016, 1981) when project auctions for the Belo Monte Hydroelectric Complex officially began. Located 52 kilometers upstream from the dam (see Figure 3.1), Altamira absorbed more than 30,000 construction and service sector workers which poured into the area at the peak of dam construction between 2012 and 2015. Population rose from 77,439 inhabitants in 2010 to an estimated 109,938 in 2016 (IBGE, 2011; IBGE, 2016). Nonetheless, people familiar with the area estimate that the actual population may have been closer to 150,000 inhabitants at its peak, settling back to 110,000 by the end of the construction peak (Marin et al., 2016; Moran, 2016).

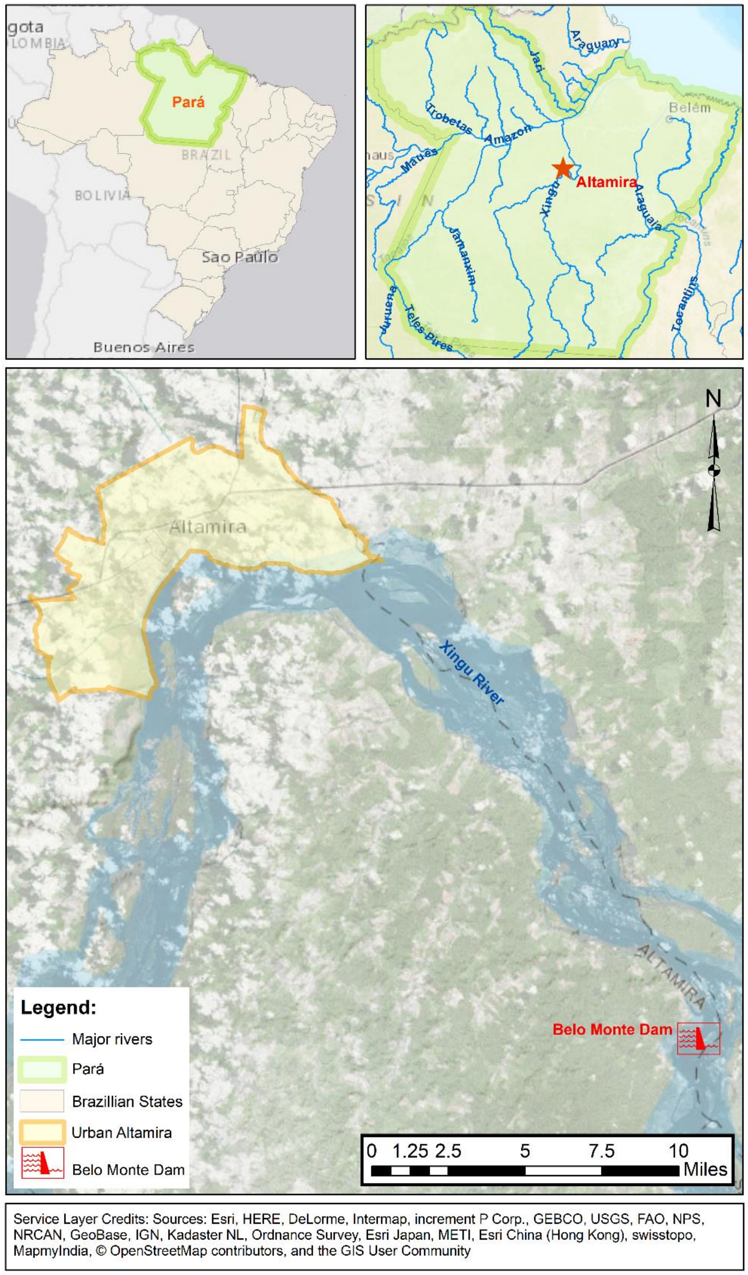


**Figure 3.1:** Altamira and Belo Monte Study Region

The city's urban area grew exponentially and currently consists of 112.87 km$^2$ containing nineteen neighborhoods (IBGE, 2016). Parts of the city, along with a segment of the Xingu River, act as partial reservoir for the dam. As a result, low laying areas in urban Altamira were flooded.

Five collective urban resettlements (RUCs) were built in vacant land within existing neighborhoods to provide housing for families displaced by flooding. These relocations, along with the population increase, augmented population density in some neighborhoods and restructured the city's layout. Figure 3.2 depicts Altamira's urban growth between 2006 and 2016. Local authorities were unprepared for the significant increase in residents, and the already lacking basic sanitation services in the city were unable to meet the demand. During Belo Monte's construction, Altamira was once again disrupted by a large infrastructure project, reminiscent of the arrival of the Trans-Amazon Highway in the 1970s (Moran, 2016).

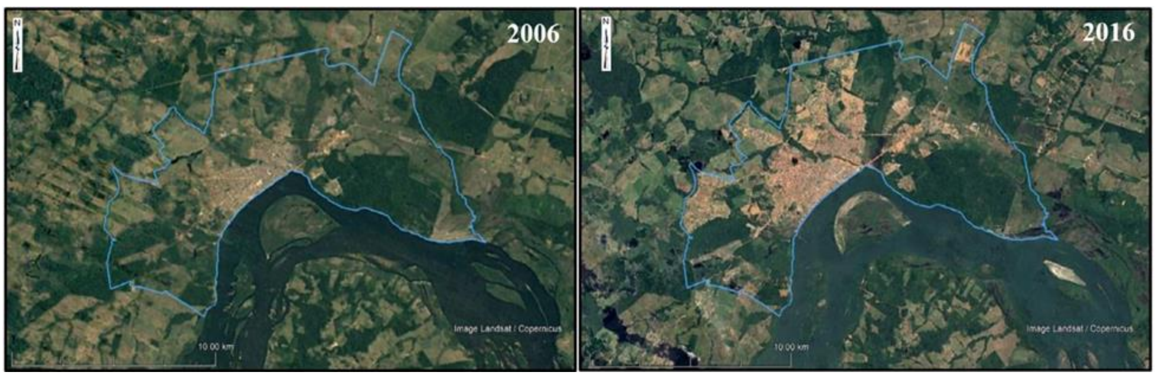


**Figure 3.2:** Urban Growth in Altamira
*(Google Earth Images)*

### *3.2.3 Basic Sanitation*

Due to the scattered occupation of the Amazonian territory and the rush to extract value from its natural resources, provision of public services has lagged behind the rest of Brazil. In the states of the Brazilian Amazon, 52% of residents receive potable water from a distribution network and only 10% are provided with sewer services (Ministério das Cidades, 2016), leading to dependence on septic tank use. Figure 3.3 shows that even the capital cities located in the Brazilian Amazon mostly use septic tanks (Brondizio, 2016).

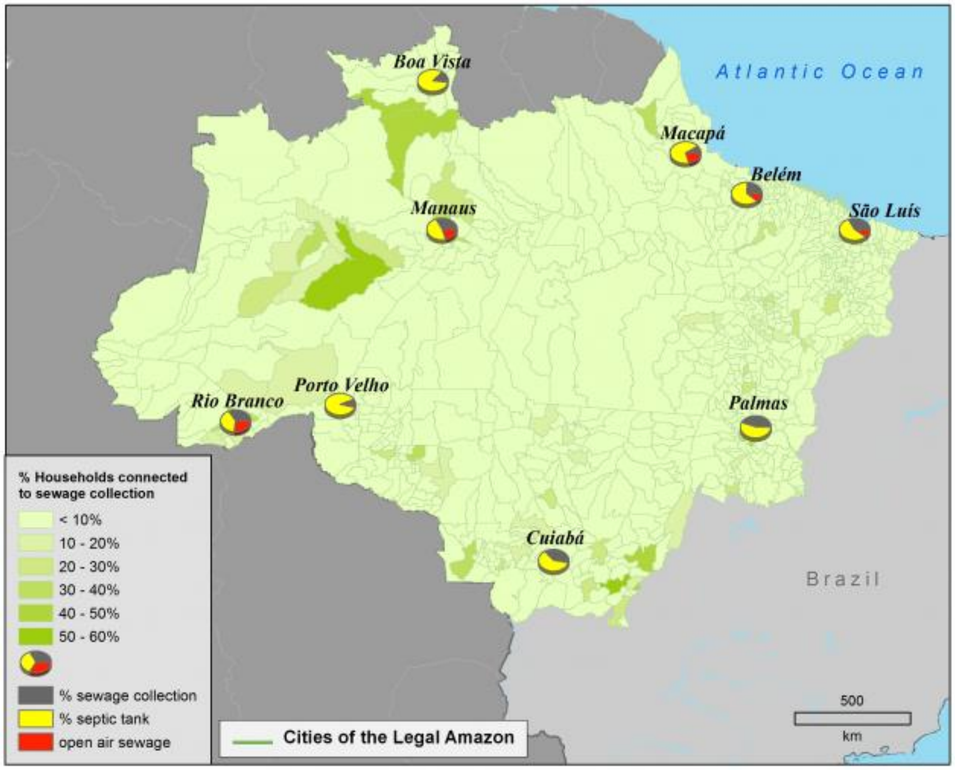


**Figure 3.3:** Proportion of households in Amazonian municipalities and state capitals connected to sewage collection.
*(Brondizio, 2016)*

Non-capital cities, such as Altamira, are even less well-served than those depicted in Figure 3.3. A single unconfined aquifer currently supplies groundwater for the majority of Altamira's urban area (CPRM Serviço Hidrogeológico do Brasil, 2014), with residents relying heavily on wells as their main source of water. Furthermore, according to the National Sanitation System, 90% of the population in the municipality of Altamira was disposing of their wastewater in alternate systems (Ministério das Cidades, 2016) with residents relying mainly on septic tanks as their primary source of wastewater disposal. These septic tanks generally have an open bottom, allowing liquids to percolate through the soil. Given that high septic system densities are associated with endemic diarrheal illnesses (Borchardt et al. 2003; Hunt et al. 2010), contaminant transport from septic tanks to water wells is of growing concern in Altamira. As the population increases, new wells and septic tanks are built and distances between new and old structures decrease. This reduces contaminant transport times from septic tanks to water wells and puts the health of the population at risk (Ministerio Publico Federal, 2016; Conselho da Justiça Federal, 2017). A visual representation of contaminant transport from septic tanks to water wells is shown in Figure 3.4.

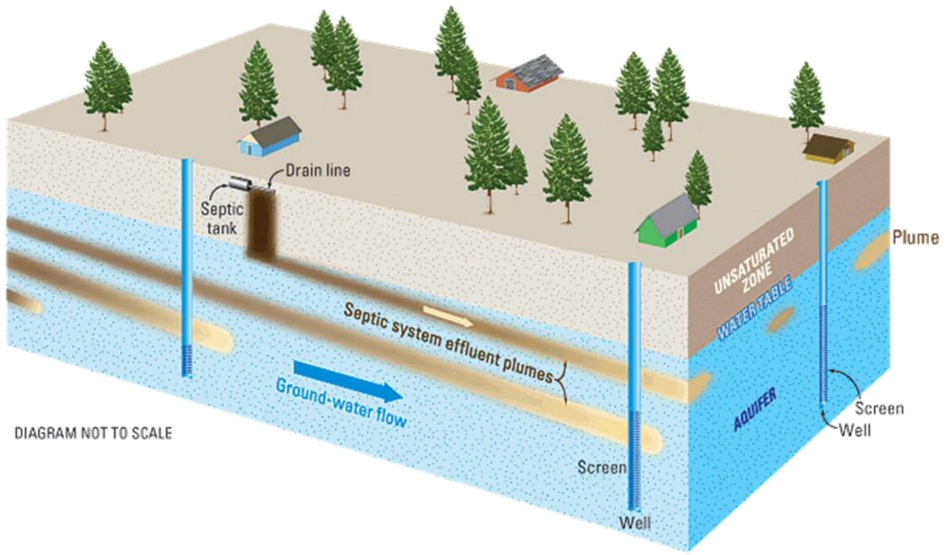


**Figure 3.4:** Contaminant transport from septic tanks to water wells
*(USGS, 2016)*

Aside from wastewater intrusion into wells, leachate from solid waste can carry contaminants to the area's water resources (Borchardt et al, 2003; Hunt et al, 2010; Ikem et al, 2002; Mor et al, 2006; Palamuleni, 2002) and rainfall induced infiltration can impact drinking water supplies. In Altamira's wet season, intense rains flood parts of the city along with low laying well heads. Therefore, basic sanitation is important in the protection of the city's water resources as overflowing septic tanks, solid waste contaminants, and feces from scavenger animals can all contribute to pollutant entry to wells.

The sanitation crisis that has erupted in Altamira was deemed critical by Brazil's Federal Public Ministry and in April of 2017, Belo Monte's Operation License was suspended until the crisis was addressed (Ministerio Publico Federal, 2016; Conselho da Justiça Federal, 2017; Harari, 2017a). In the environmental licensing process, the urban residents of Altamira were promised potable water and an adequate sewage system that would improve previous sanitation conditions and quality of life (IBAMA, 2015). These services, however, have yet to be delivered in their entirety. However, the judicial decision that suspended Belo Monte's license was not effectively enforced as the dam continues its daily operations (Harari, 2017b). In this sense, Belo Monte exemplifies one of the disconnects between national policy and local reality in Amazonian large hydropower developments that will be further explored in this paper.

The similarity in provision of services and waste disposal practices throughout the region leads us to believe that, if left unaddressed, the implementation gaps we will discuss in this paper are likely to emerge in future hydroelectric development projects currently envisioned throughout the Amazon Basin. As more dams in the Amazonian region are planned, identifying public policy implementation gaps that affect basic sanitation and water resources creates opportunities to anticipate problems that could impinge on the public health needs of residents where such large infrastructure projects will be implemented.

### 3.3 Existing National Public Policies

In Brazil, divergent patterns of development exist across regions, and evaluation of development at a local scale remains a major challenge for public policy and administration. An important task that aids in examining local development is coming up with precise definitions of what types of policies should be included in assessing local development projects (Barberia et al, 2010). Using Brazil's National Water Resources Policy and Federal Basic Sanitation Law, we can assess Belo Monte's success in delivering a better quality of life to the population in Altamira through adequate water provision and sanitation services. It is not our goal to provide detailed descriptions of each of these policies, but to briefly discuss them in order to succinctly state their main goals and requirements.

### *3.3.1 Brazil's National Water Resources Policy*

Established in 1997, Brazil's National Water Resources Policy (Law No. 9.433 / 97 – Política Nacional de Recursos Hídricos – PNRH) is one of the main instruments guiding water management in the country. The PNRH is comprised of guidelines, goals and programs reviewed and approved by the Ministry of the Environment's National Water Resources Council. While it faces challenges in its applicability to attend to all with equity (Wolkmer and Freiberger, 2013; Caubet, 2006), it provides basic requirements that would improve the water and sanitation of communities in Brazil if its demands were adequately fulfilled.

The objectives of this plan are to ensure: 1) the necessary availability of water to current and future generations in quality standards appropriate to their uses, 2) the rational and integrated use of water resources, including water transport, with a view toward contributing to sustainable development and, 3) the prevention and defense against critical hydrological events of natural origin or arising from the inappropriate use of natural resources. According to the Ministry of the Environment, the overarching objective of the PNRH is "to establish a national pact for the definition of guidelines and public policies aimed at improving the supply of water in quantity and quality, managing the demands and considering that water is a structuring element for the implementation of sectoral policies from the point of view of sustainable development and social inclusion " (Ministério do Meio Ambiente, 2016).

The PNRH is periodically reviewed and adapted to fit the realities of 12 national hydrographic regions in Brazil, based on technical analyses and public consultations. Each hydrographic region should have its own committee that approves a Basin Water Resource Plan (Presidencia da República, 1997). Each committee should count with various representatives from the public sphere (national, state and municipal), users (industry, irrigation, water supply, power generation, etc.) and civil society (Jacobi et al, 2005). In cases where there are designated indigenous lands within the basin, the National Indian Foundation should also take part in the committee. Basin committees are also in charge of mediating water-related conflicts on a first administrative instance, as well as establishing mechanisms and suggesting price tariffs for the use of water resources (Agência Nacional de Aguas, 2011).

Although the holistic perspective of this policy cannot present a single solution for different socioeconomic contexts, it remains a useful instrument that provides recognition of basic water resource requirements for the Brazilian population. Failure to meet PNRH objectives will be discussed as we uncover the situation in Altamira.

### *3.3.2 Federal Basic Sanitation Law*

Under Brazil's Federal Basic Sanitation Law (Law No. 11.455 / 07), basic sanitation constitutes a set of services, infrastructures and operational facilities for the public supply of drinking water, the adequate disposal of sanitary sewage, solid waste management, and urban stormwater management. Brazil's Federal Basic Sanitation Law, establishes national guidelines for the Federal Basic Sanitation Policy. One of the objectives of this policy is to "minimize environmental impacts related to the implementation and development of basic sanitation services, and ensure that they are carried out in accordance with the norms related to the protection of the environment, land use and occupation, and health." (Presidencia da República, 2007)

The fundamental principles for the provision of such services include, but are not limited to, the universalization of their access; methods, techniques and processes that take into account local and regional peculiarities; services being appropriate to public health and environmental protection; integration of infrastructures and services with efficient management of water resources; the safety, quality and regularity of such services; and their "articulation with urban and regional development policies, environmental protection, health promotion and other relevant social interest policies aimed at improving the quality of life for which basic sanitation is a determining factor." Regional plans for the provision of services must be elaborated and executed in articulation with the State, Federal and Municipal entities involved. Federal, state, and municipal integration stimulates the implementation of infrastructures and services common to Municipalities, through mechanisms of cooperation between federated entities.

The construction of the Belo Monte dam offers an ideal case study to understand the challenges in scaling down and implementing these national laws and policies. The investments attached to the construction of the Belo Monte dam was an opportunity to bring basic sanitation to a region historically characterized by precarious provision of these services. Instead, there has been a failure to comply with national policies. The processes witnessed in Altamira and discussed in this paper are being replicated in the construction of other dams in the Amazon region, giving added urgency to addressing these issues. Similar projects loom in the region, and adequate implementation of policies is crucial to avoid future sanitation crises caused under the rapid changes brought forth by large development projects. In the following sections, we will examine Altamira's current situation and identify tenets in the national laws that are not being addressed.

### 3.4 Data Collection and Methods

In order to determine Altamira's current basic sanitation services, surveys to the population and semi structured interviews with government officials were carried out in July 2016. Surveys included questions relating to current services provided to the household, the primary source of potable water, wastewater disposal methods used and solid waste collection frequency. The distribution of the surveys was determined by using the "Probability Proportional to Size" method (Graham 1983, Groves 2009, Randell et al, 2014), where the probability of selecting an element is directly proportional to its size, or in this case, the probability of selecting a household is directly proportional a neighborhood's population density. The sample was further stratified by altitude to ensure households in varying elevations were being surveyed. Data on individual neighborhood and total urban populations were gathered from the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2016) to determine population density per neighborhood. Information on elevation was gathered from Google Earth imagery and corroborated through the use of a global positioning device in the field.

Ultimately, 130 surveys were performed in the 13 most populated neighborhoods of urban Altamira (see Figure 3.5). Sampling these particular neighborhoods yields an accurate representation of the services Altamira residents receive. Given time restraints and limited field assistance, the remaining 6 neighborhoods were excluded from the scope of this study due to their low population. At the end of each survey, coordinates and elevation were collected for each household using a global positioning device to precisely locate them on the urban landscape. Observed community groundwater wells and solid waste dumping locations were also recorded. Figure 3.5 shows the location of the households surveyed along with Altamira's neighborhood boundaries.

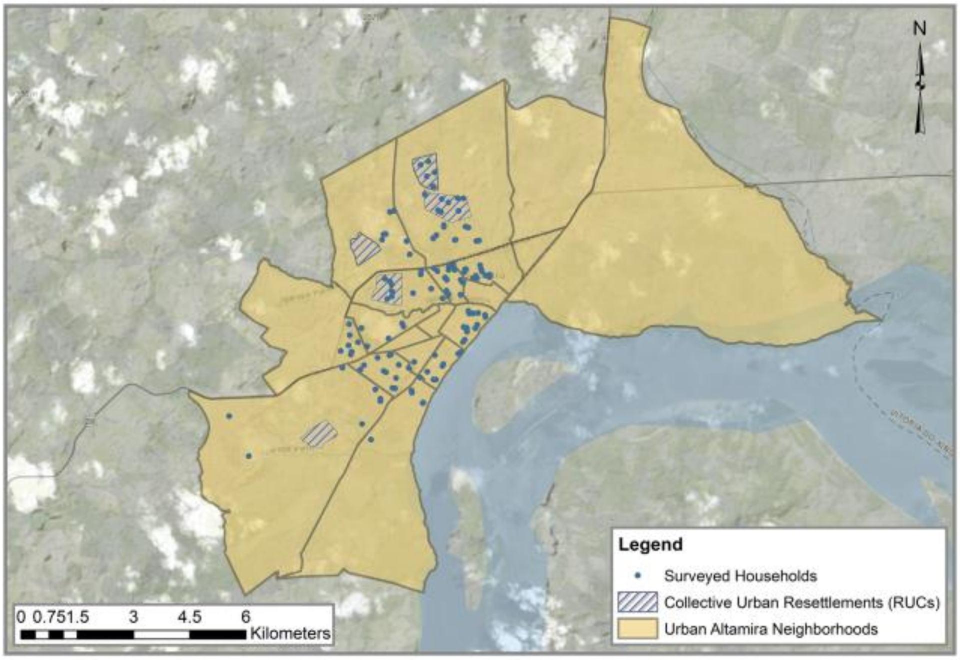

**Figure 3.5:** Location of households surveyed, neighborhoods boundaries, and collective urban resettlements (RUCs)

In addition, semi-structured interviews were performed in June and July of 2016 with the following local offices and government branches: Brazilian Institute of Geography and Statistics (IBGE), Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), Secretariat of the Environment (SEMAT), Public Sanitation Department (DLP), Norte Energia, Altamira Sanitation Company (COSALT), and Secretary of Urban Planning (SEPLAN). Questions relating to the current services provided, and hindrances in their provision from each local office standpoint were discussed. Local population behavior and impressions in relation to water and waste services were also observed during the fieldwork period. This complemented the information collected in the surveys, acting as a bridge to help further understand Altamira's basic sanitation services. Publicly available information regarding public policies, laws, project licensing, reporting, and other legal documents were obtained from government websites such as IBAMA, the Office of the Federal Public Prosecutor, and National Sanitation Information System.

ArcGIS Desktop 10.5 software was used to generate the maps presented in this paper.

STATA 14 software was used to create summary statistics of potable water service provision and frequency, wastewater and greywater disposal methods, and solid waste collection frequency.

## 3.5 Results

### *3.5.1 Availability of Potable Water*

Although Altamira is located on the banks of the Xingú River and has a potable water-treatment plant, 79% of the households surveyed get their drinking water (either regularly or occasionally) from wells. Figure 3.6 shows the surveyed households that have a well. This highlights the importance of household surveys in distinguishing between water resource *access* and water resource *use*. Depth of wells range from 3.9 meters (13 feet) in low lying neighborhoods to 28 meters (92 feet) in higher elevation areas. The most common treatment of drinking water was found to be chlorination and/or boiling. However, during the wet season, groundwater levels rise (IBAMA, 2010) and residents report degradation in the quality of water with observable turbidity and a distinct smell, regardless of treatment. Shallow wells tend to be dug by residents or independent "well-diggers" that offer their services (see Image 1). Such wells are not coated and are at risk for intrusion of contaminants. Interviews revealed that wells that are coated with layers of sand and rock have a cost of $13 dollars per foot (per 0.3 meters). This makes deep wells, which are less susceptible to variations in the dry months, a costly matter for most households.


**Figure 3.6:** “Well digger” making a household well.

The city’s water treatment plant only served 35% of the households sampled, of which only 18% reported continuous and reliable service to their homes. During semi-structured interviews with Altamira’s Sanitation Company (COSALT) it was disclosed that the water treatment plant is operating at well over half capacity, although not everyone in the city is yet connected to the network. Norte Energia, Belo Monte’s construction consortium, made improvements to the city’s already existing water treatment plant and water distribution network. While Norte Energia provided infrastructure and equipment to expand the water treatment plant operations, limitations remain. Particularly, the water treatment plant’s aerator volume can sometimes be a limiting factor in the amount of water that can be treated per day. Further, a series of lift stations with inadequate pump capacity were installed, preventing higher altitude neighborhoods from receiving city water.

Out of the 13 neighborhoods sampled, 7 relied on private wells for their potable water, only one was connected to the distribution system, and 5 neighborhoods had partial connections. In partially connected neighborhoods, areas not receiving services have wells or are supplied water by tank trucks. According to interviews, tank trucks do not possess a fixed water distribution schedule and may come anywhere between one to two times per week. In some instances, it was reported that the tank truck driver would charge residents for the distribution of water.

Households located in the 5 recently built RUCs are not meant to have private wells, although some residents have attempted to build their own. These RUCs receive water through a shared community water tank and distribution network. COSALT and Norte Energia have built community wells to supply water to the community water tanks. However, in 3 out of the 5 RUCs these wells are supplemented with tank trucks to fulfill the water demand of the residents.

Each neighborhood faces different challenges in their water supply and this diversity of situations within neighborhoods make facile generalizations difficult. Still, the unreliability of the water distribution system is one very important driver for the dependency on household wells, according to the households interviewed. Irregular or no connection to the local water distribution system increases the dependency and density of water wells for all neighborhoods in Altamira.

### *3.5.2 Wastewater Treatment*

All households in Altamira lacked a connection to wastewater treatment. Seventy-eight percent of surveyed residences disposed of their wastewaters through septic tanks. The only ones with some disposal were households located in the 5 recently built RUCs. Households located in these resettlement neighborhoods collected their waste in aboveground community tanks which were emptied and hauled to the wastewater treatment plant. The wastewater treatment plant, financed by Norte Energia, only serves these 5 locations while the rest of the city entirely lacked wastewater treatment service. This can be observed in Figure 3.7, where no use of septic tanks was reported in the households surveyed within the RUCs.

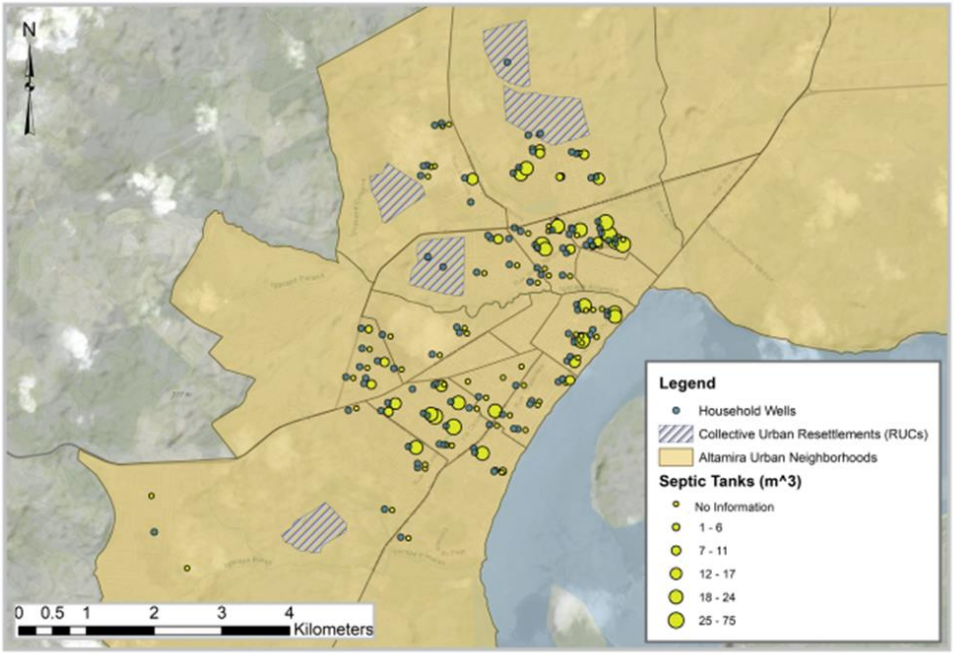


**Figure 3.7:** Septic Tank Volumes and Well Locations of Surveyed Households

Of the households using septic tanks, 63% were constructed by current residents, family members, past owners, or local independent handymen. Only 4% of the septic tanks had been constructed by a septic tank company or by the municipality. Figure 3.7 shows the range of volumes of the septic tank found as reported by the residents of the households surveyed. Interviews revealed that septic tanks tend to lack an impermeable bottom and allow for percolation of wastewater to the soil and groundwater, representing a great risk for the cross-contamination to water wells. Greywaters not coming from bathrooms were reported to be discharged directly to the surface or neighboring water bodies in 57% of the households. Interviews revealed that the potable water treatment plant discharges residual filter wash waters (waters used to wash the filters) directly to the surface. Reports show that local commercial and business interests, including the hospital, discharged all non-bathroom greywaters in that same manner (Ministério Público Federal, 2016). Direct discharges onto the river were routinely observed by the research team and reported by civil society on many previous occasions, to no effect. Interviews and surveys conducted in

June and July 2016 revealed that connections to a sewage network had not started. Connections to households began at a slow pace approximately 14 months after our fieldwork concluded, but they did not include collection of greywaters.

### *3.5.3 Solid Waste Management*

All but one household surveyed was served by solid waste collection services. Collection took place directly from the front of their homes in 94% of the residences receiving services. Alternative methods of solid waste disposal were used in 23% of the households and included burning, burying, dumping in an empty lot, and dumping in a body of water. The main reasons reported for these alternative disposal methods were: 1) to minimize accumulation of wastes in the home, and 2) lack of collection of certain materials (i.e. yard wastes, metal scraps, Styrofoam) by the current collection services. A daily frequency of solid waste collection was reported for 27% of the homes and a frequency of two to three times a week was reported in 68% of the households. Altamira's solid waste collection is not performed at a consistent time of day, which leads residents to leave their refuse in front of their houses for long periods until trucks come. In the meantime, animals, mainly dogs and vultures, break the plastic garbage bags and spread solid waste which in some cases enters the stormwater system given the high and frequent precipitation of this rainforest region.

Prior to the construction of the dam, Altamira's Public Sanitation Department (DLP) had a fleet consisting of 6 compactor trucks and 7 open top trucks. Norte Energia provided an additional open top truck, one compactor truck, and one 40-yard container. All trucks are in rotation and operate daily, rotating between urban neighborhoods and peripheral rural areas. According to Altamira's DLP, 40 tons per day of domestic waste were collected before Belo Monte, increasing to 110 tons per day during dam construction, and currently leveling at 80 tons per day. There was no doubling of trucks to collect the increase in garbage produced by urban and peri-urban residents. Norte Energia provided a new landfill to accommodate the increase in construction and domestic waste. They also performed closure and remediation activities for the old landfill, installing groundwater monitoring wells to monitor possible pollution. Interviews with the Secretariat of the Environment (SEMAT) revealed that the monitoring for these wells is difficult, due to constraints in laboratory services in the city.

## 3.6 Discussion

Aside from the survey results presented in the previous section, the semi-structured interviews revealed crucial insights to hindrances experienced by local agencies in the provision of services to the residents of Altamira. These interviews uncovered an intricate nexus between political, social, and environmental elements which shape Altamira's current situation and identify hindrances to the provision of better water and sanitation services.

### *3.6.1 Resource Allocation*

Interviews performed revealed that Altamira's local Brazilian Institute of Geography and Statistics (IBGE) offices were not given any financial or human resources to conduct a mid-term census and cannot provide official, verified information regarding the new population that came to Altamira after the 2010 census was performed. Formal IBGE estimates are based on national calculations that do not take into account population booms brought forth by big scale development projects such as Belo Monte. This leaves all other agencies not knowing the population to be served. Without a reliable source for the number of inhabitants, agencies providing services are left in the dark and are unable to justify changes to their budgets to address the change in demand. Implementation of a national scale census is not possible, thus, a more localized approach to better estimate and determine the current population in the city is needed. People familiar with the area contended that the population during Belo Monte's construction peak was between 110,000 and 150,000 (Marin & Oliveira, 2016; Moran, 2016). Acting on such estimation would have been preferable than the dithering by agencies over the lack of a precise census count.

Furthermore, understaffing is an issue pervasive in the local government agencies interviewed. Particularly, Altamira's Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) office counted with only three technicians at the time of this study. Given the magnitude of the project, legal matters and paperwork regarding Belo Monte's Operation License and environmental compliance is mainly administered and overseen at a national level by IBAMA's headquarters in Brasilia, located approximately 2,000 kilometers away from Altamira. Local IBAMA technicians are largely battling the ever-present threat of deforestation in the region, which is a feat in itself. Hence, the already limited amount of technicians working at Altamira's IBAMA offices are deterred from engaging in compliance matters at a local level to report to the national office in regards to Belo Monte. This creates a gap between what is happening at the local scale, and what is reported to the agency at the national scale.

Interviews also revealed that equipment available to service the population in the collection of domestic solid waste is a limitation for Altamira's DLP. At the time of the interviews, all trucks were in rotation and operated daily, with no margins for malfunctions or flat tires. Altamira's DLP fleet consists of 7 compactor trucks and 8 open top trucks. In the case of such drastic population increase in Altamira, a significant increase in equipment for public sanitation would have been appropriate since an increase in domestic solid waste is to be expected. Solid waste collection strategies have struggled to efficiently manage the increase in population. The lack of equipment feeds into disrupted collection schedules, which at times can be inconsistent in collecting and handling the increasing solid waste generation in Altamira. Interviews revealed that the city budget will most likely not allow for any additional workforce increase in the DLP, or for revisions in solid waste collection strategies. This will add to an already undersupplied and underprovided solid waste collection service, deterring the department from providing quality services to the population.

Although investments in the infrastructure of the Amazon region have been made by the national government to generate rapid economic growth, the Amazon region trails behind the rest of the country in water and sanitation services. In the 1960s and 1970s, Brazil borrowed from international creditors for industrialization and infrastructure programs, including urban water systems, but aging water infrastructures and growing demands in the region now put great pressure on federal budgets. Water systems have been passed to the state level and, due to the long term and the capital-intensive nature of water infrastructure, there is a general disincentive to make long-term investments for water networks (Swyngedouw, 2005). In the same way that the city budget does not allow for additional DLP staff, the state and local offices all claim lack of funds for the operation and maintenance of Altamira's water distribution network. The state agency in charge of potable water systems in Pará (COSANPA), passed the water system responsibilities to the city of Altamira (COSALT), whose budget is also insufficient to serve the growing population. Initial investments in the sanitation services, including water, were made by Norte Energia. However, after completing its mandated post-dam construction obligations, Norte Energia will eventually leave and Altamira will be left with a smaller local budget that will unlikely sustain long-term fixed capital investments or system maintenance.

A much greater population is being served without markedly improved organization or infrastructure. Integration of infrastructures and services along with efficient management of water resources is crucial to development, yet sorely lacking in Altamira. In this sense, national scale policies such as Brazil's National Water Resources Policy (PNRH), Basic Federal Sanitation Law, and Belo Monte's Environmental Licenses, ultimately failed to be implemented in a manner that considered legal requirements, local patterns of water management, household water demand, and basic sanitation practices.

### *3.6.2 Licensing and Retributions*

Environmental impact assessments (EIAs) are embedded in politics and are imagined as sites of power relations (Spiegel, 2017). EIAs and public policies are crucial instruments for environmental management, yet their entanglements in political processes and associated power structures can hinder these goals. One example is the ongoing national government investigation for inappropriate forms of payment coming from Odebrecht, Belo Monte's main construction company, to the political party under which licensing for the dam was granted. This added component suggests that environmental licensing processes and public policies can be interfered with, disrupting their main objectives and adding yet another dimension to an already complex licensing, oversight, and retribution structure within big development projects. Furthermore, and not unlike other countries, project documents may uphold principles of justice but national political priorities may well override these principles. The degree of administrative and political control from central governments and its obverse are key factors which shape justice outcomes in environmental projects. (Blaikie, 2014).

The Belo Monte dam was granted a Construction License under the condition that Norte Energia would improve the water and sanitation systems used in urban Altamira. The company had not yet met this requirement after 4 years of construction, yet was granted its Operation License (IBAMA, 2015). Belo Monte's Operation License approved the dam's reservoir to be filled and the turbines tested. Since the Operation License was granted regardless of previous unfulfilled requirements, it mandated that before filling the dam’s reservoir, all septic tanks and water wells were to be cleaned and closed and other inadequate forms of sewage disposal systems were to be eliminated. Additionally, a formal connection of all households to the potable water network was supposed to be established. The Operation License dictated that by September 30, 2016 all households in urban Altamira were to be formally connected to the potable water network and sewer system (IBAMA, 2015). Norte Energia was expected to begin wastewater inter-domiciliary connections in July 2016 (Norte Energia, 2016), leaving only 3 months to connect roughly 15,440 households. As of 2017, these conditions had not yet been met, not all households were connected to potable water or sewer systems. IBAMA granted the Belo Monte dam’s Construction License and Operation License disregarding the basic sanitation conditions required by both licenses and by Federal law. Partial flooding of the city and population growth added pressure to Altamira’s already stressed water and waste management systems, creating a public health crisis. In light of this, the Federal Public Prosecutor filed a Public Civil Action Suit in March 4, 2016. The suit revealed that no detailed studies regarding the Altamira water table were made in the environmental licensing process and it questioned Belo Monte’s compliance with the Basic Environmental Plan submitted early in said licensing process. Specifically, it raised inquiries on the provision of potable water, sanitary sewage, drainage of urban rainwater, and urban solid waste management. The immediate suspension of the Operation License was requested until the sanitation conditions were met, and daily fines were imposed. Norte Energia was also retroactively fined 2,500,000 reais (approximately $773,000 USD) for direct sewage discharges from the Jatobá collective urban resettlement. Moreover IBAMA has fined Norte Energia 27 times, totaling 76,183,605 reais ($23,625,263 USD). This includes a 7,500,000 reais ($2,325,986 USD) fine for failing to provide household connections to a sewage system in urban Altamira (IBAMA, 2017).

Although water is a public good, its degradation becomes an externality that is not taken into account because there is no market value imputed; governments and businesses are unable to internalize the true value of its degradation (Schomers, 2013). The suits and fines imposed on Norte Energia were not severe enough to halt the operation of the dam nor change sanitation for city residents. Delivery of adequate potable water and effective sewer system services was not completed as observed from the unfinished pipe network, inadequate booster pump capacity, and a water treatment plant with limited volume to handle demand. These are some of the factors that prevent the universalized access and hinder the safety, quality, and regularity of basic sanitation services, mainly potable water, being provided to residents. Belo Monte continues to operate without fulfilling licensing requirements, PNRH, nor Basic Sanitation policies. The energy sector has long used the narrative of an impending energy crisis as justification for overlooking social and environmental impacts and justifying approval of projects questioned by social and environmental impact statements (Boanada Fuchs, 2015; Boanada Fuchs 2016). Legal requirements need to be executed to protect the health and wellbeing of the population and minimize environmental impacts related to the implementation and development of sanitation services Stronger measures are needed so that environmental enforcement of existing laws and regulations have sufficient power to stop construction or operation until legally mandated conditions are fulfilled.

### *3.6.3 Regional Practices*

Generally, once a dam is approved, construction moves very quickly. Equipment is rented on a 24-hour basis and engineering firms are given incentives to finish ahead of schedule. This pace is diametrically incongruent to that of government agencies in charge of building hospitals, schools, health posts, and other public services. Government agencies are reluctant to use their budgets, which rarely foresee the eventuality of a major project being built in their area. These agencies also have unclear boundaries to their duties, or in some cases they have overlapping responsibilities. State and local governments do not receive additional federal funds for the population increase, since federal allocations are based on the decadal census. In the case of Altamira, within months of the 2010 census, the data was no longer relevant due to the explosive growth in population brought forth by Belo Monte's construction. The lack of official figures for Altamira's population resulted in an unwillingness by the government, at all levels, to provide emergency funding to meet urgent needs. Claiming budgetary constraints, local, state and federal agencies refused to step into this data vacuum and, rather than attempting to quickly address these data deficiencies, a certain bureaucratic immobility set in. The indisposition and apparent inflexibility at a national level to perform a midterm census, or go by informed estimates, was used as justification at a local scale to avoid acting promptly to resolve the matter.

Aside from these issues, there are of course greater social processes that shape Amazonian development. Amazonian development priorities maintain its extractive history: producing wood and spices during the colonial period, rubber in the late 19$^{th}$ and early 20$^{th}$ century, and since the model of development pushed by the military regimes of the mid-20$^{th}$ century, sending minerals and energy to the developed parts of the country. Processes such as decision-making authority, state power, capital flows, resistance by social movements, and the environmental value placed on the rainforest have changed but the course has been remarkably constant. Political interests have advanced their agendas, pursuing an increase in Brazilian national power and a greater influence on the global stage at the same time that capital and market forces at an international scale have influenced the course of development in the Amazon (Brown et al., 2005). The expansion of cattle has been moving inexorably towards the Amazon, as areas of pasture in the South East and Central

West have been converted to production of sugar cane for ethanol, and soybeans for export. Most of the hydropower produced in the Amazon goes to industries and urban regions in the developed regions of Brazil, while the Amazon population remains with little voice in these development processes, saddled with severe impacts on its forests and rivers, and without the expected improvements in livelihoods, or in water and sanitation (Morton et al., 2006, Fearnside, 2001). The migrations that occurred in Altamira are part of the social processes that result from large development projects such as Belo Monte. In Altamira, these migrations doubled population and, coupled with non-compliance of public policy and environmental regulations, impacted basic sanitation provision.

At a regional scale, Altamira is no different than many other small cities in the Amazon. National decisions disregard the needs of the population in the region, concerned as they are with aggregate economic growth in the urban-industrial parts of the country (Walker et al., 2000). The population remains highly dependent on septic tanks for their wastewater management (Brondizio, 2016). Therefore, it is no surprise that closing of all groundwater wells, septic tanks, and other sewer disposal systems has met opposition from civil society. Residents are ill disposed to pay for sewage charges if they have never had to do so before and are reluctant to give up their wells to connect to an unreliable potable water system. At the time this article was written, Altamira's municipality was trying to introduce a payment schedule for water service that charges households nearly the same as businesses or industries. The population was appalled by this price schedule, particularly when services continue to be unreliable. Taking these local characteristics into account can help aid in anticipating pushbacks from residents hesitant to connect to a sewage or potable water system. While these disposal techniques may have been used in the past, the introduction of a large development project, along with the population boom it brings to the area and the regional practices of waste management, further amplifies risks to local water resources by increasing contaminant flows into the watershed. Thus, implementation of basic sanitation services appropriate to public health and environmental protection are imperative, however, deficient in Altamira.

### *3.6.4 Environment and Public Health*

Current practices in Altamira lead to the degradation of its two main water resources: the local aquifer and the Xingu River. Sanitary discharges from septic tanks to the local aquifer and greywater discharges to the Xingu River infringe upon Brazil's PNRH objectives of maintaining availability of water to future generations in quality standards appropriate to their uses, as well as failing to prevent critical hydrological events arising from the inappropriate use of water resources. An attempt at monitoring the local resources was, however, done by Norte Energia. As per Brazil's PNRH, Norte Energia instituted a Water Resource Plan that established actions to minimize and monitor impacts on surface and groundwater resources. The plan included monitoring programs and schedules for water quality testing of superficial waters and groundwater. Norte Energia also installed groundwater wells to monitor possible pollution in the old city landfill which was remediated and closed. However, monitoring was deferred to the Secretariat of the Environment (SEMAT). Interviews with SEMAT personnel revealed that the closest water laboratory able to perform the water quality testing required in the Water Resource Plan is located in the capital city of Belém, 460 kilometers northeast of Altamira and, due to this difficulty, they have been unable to continue the monitoring schedule. The fact that there is no adequate water laboratory in Altamira to carry out the requested water quality tests shows that there is a disconnect between national planning and local capacity to carry out the legal mandates. This is yet another instance in which local and regional particularities were not taken into account. Using methods, techniques, and processes that take into account local and regional peculiarities is, in fact, one of the fundamental principles stated in Brazil's Basic Sanitation Law.

The environmental impacts of policy noncompliance on public health can be observed in the sanitation crisis in Altamira. Although different neighborhoods face distinct challenges in the fulfilment of their basic sanitation needs, the diversity of situations still reveal a lack of implementation of existing legislation. Irregular services to households, potential contamination of groundwater, and direct discharges to the Xingú River, shows that the PNRH's overarching objective - improving water supply in quantity and quality, managing water demands, and considering sustainable development and social inclusion - is nowhere close to being fulfilled. Moreover, multiple fundamental principles for the provision of basic public sanitation services are not being met. These include the universalization of access to services; methods, techniques and processes that take into account local peculiarities; services appropriate to public health and environmental protection; infrastructure and services with efficient management of water resources; the safety, quality and regularity of services; and articulation of services with environmental protection, health promotion and other policies aimed at improving the quality of life for which basic sanitation is a determining factor. The basic sanitation services found through our research in Altamira certainly do not ensure the protection of the environment and health.

### 3.7 Conclusions

Amazonian development plans to increase energy production for the benefit of the country have overpowered environmental conservation at a regional level, quality of life at a local level, and protection of water resources as dictated by the national public policies discussed in this article. Dam development projects backed by international and national lenders steamroll local and regional concerns. In projects such as Belo Monte, international funds are accepted nationally along with the project document, which may uphold principles of justice, but national political priorities may well override these principles at all levels. Thus, in many cases, justice issues are treated as rhetoric and ignored (Blaikie, 2014). Current implementation of public policies and laws have ignored the population most affected by the construction of the dam, basic permit conditions were not satisfied and yet the dam was built and continues to operate. We have established that environmental variables can combine with resource allocation, regional practices, and licensing and retributions to impact basic sanitation services and thus, public health of the population. Recognizing that such political, social, and environmental elements play into the provision of adequate services, we believe there is a necessity to ensure that current laws and policies are followed and that resources to cope with the doubling of population and their waste are provided as a condition for building hydroelectric projects in the region.

The relationships between local and national levels of government continue to place national energy needs ahead of the most basic human needs of the Amazonian population. The relationships between national, regional, and local scales obfuscate adequate implementation of overarching policies mandated to protect against environmental degradation and provide a suitable quality of life to the population. As with the case of Altamira and the Belo Monte dam, the conditions required and dictated by the discussed national policies differ from local reality and appear to be disconnected. National policies for the provision of basic sanitation services and protection of water resources must take into account local and regional circumstances and financial capacity at the time of their implementation and provide the funds to carry out their obligations. Failure to consider these particularities, and attempting to implement national scale approaches without ensuring a timely provision of funds at the right scale for implementation, has prevented mechanisms of cooperation between different levels of government and private entities from functioning to the benefit the population. Integration of federal, regional, state, municipal, and city levels in the analysis of implementation of policy increases the chances of properly executing them, especially when additional coordination is required with private entities in charge of the dam construction and management. Furthermore, payments to political parties in return for favors are not unusual, even in developed countries, in the area of basic sanitation services (Swyngedouw, 2005). Ensuring stern consequences at all levels for noncompliance with basic sanitation policies is essential in administering change and providing adequate basic sanitation services, environmental protection, health promotion, and other social interests that result in improving the quality of life of the population.[4]

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## FECAL MARKERS AS INDICATORS OF SANITATION IMPACTS TO GROUNDWATER STEMMING FROM LARGE HYDROELECTRIC PROJECTS IN THE AMAZON.

### 4.1 Abstract

Communities hosting large development projects are faced with increased population densities that place severe pressure on their water and sanitation infrastructure. In the Brazilian Amazon Basin, large hydroelectric projects are generally hosted in small cities where the significant increase in population and growth of neighborhoods brings forth greater water demand and waste disposal. Using statistical and spatial approaches, this study investigates the impacts to groundwater quality in a city experiencing the development of a large hydroelectric project. Thirty household wells in Altamira, located in the state of Pará, were sampled and tested for fecal contamination using Eschericia coli (*E.coli*) and *Bacteroides thetaiotaomicron (B.theta).* During the dry season, *E. coli* was present in 63 percent of the households sampled, demonstrating the existence of fecal contaminants in the local groundwater resources. *B.theta* was found in 43 percent of the households sampled, indicating that some of the fecal contaminants reaching local groundwater resources are human in nature. An increase in the number of homes with presence of *E.coli* was observed during the wet season, suggesting rains increase the spatial reach of this contaminant. The densest populated areas show an increase in *B. theta* concentrations during the wet season, where rains may enhance contaminant transport. Identifying the areas and seasons where there are increases in fecal contaminants can aid in the potential reduction of negative impacts to groundwater resources emerging from hydropower development not only in the Brazilian Amazon, but globally.

### 4.2 Introduction

Ensuring access to affordable, reliable, and sustainable energy for all is one of the main Sustainable Development Goals (SDGs) established by the United Nations (United Nations, 2018). One target of this SDG is to substantially increase renewable energy globally by 2030. Hydropower plays a leading role in the sustainable energy portfolios of developing countries (International Energy Agency, 2016). At least 3,700 major dams, each with a capacity of more than 1 MW, are either planned or under construction, primarily in countries with emerging economies (Chen et al., 2016; Zarfl et al., 2015).

The proliferation of dams is most evident in the Amazon, Congo, and Mekong Basins, where proposed projects continue to emerge in order to harvest these countries' hydroelectric potential (Moran et al., 2018; Winemiller et al., 2016; Zarfl et al., 2015). Particularly in Brazil, the dependence on hydropower is substantial, providing 65.2 percent of the nation's total domestic electricity (Ministério de Minas e Energía and Empresa de Pesquisa Energética, 2015). Brazil has set its sight towards the Amazon Basin, the planet's largest drainage basin, as the future of energy production through hydropower. The Brazilian Amazon alone holds 42.2 percent of the country's total hydroelectric potential (Ministério de Minas e Energía and Empresa de Pesquisa Energética, 2015; Soito and Freitas, 2011).

There are currently over 100 dams planned in the Brazilian Amazon Basin as part of government strategies to increase energy security, economic growth, and industrialization (Luporini and Cruz, 2015; Timpe and Kaplan, 2017; Zarfl et al., 2015). Further, Brazil's National Energy Plan for 2024 details additional projects through the basin (Empresa de Pesquisa Energética, 2014b).

### *4.2.1 Impacts of large dams - Population Growth*

While Brazil looks to hydropower as a reliable renewable energy source, the negative social and environmental impacts of dams and other large developments in the Amazon Basin have long been pointed out by scholars (Fearnside, 2014, 2006; Moran et al., 2018; Moran, 2016, 1981; Smith, 1982; Soito and Freitas, 2011). One of main discussions about the negative impacts linked to large developments in the Amazon region is the significant increase in population (Dos Santos Franco et al., 2018; Fearnside, 1999; Moran et al., 2018; Moran, 2016). Previous dam development projects in the region [e.g. Tucuruí Hydroelectric Dam] have shown up to six-fold increases in population within the immediate areas of construction, reaching double the original population in ten years and severely straining the infrastructure of the area (World Commission on Dams, 2000). This is mostly due to large inflows of migrants looking for construction or construction-related employment (Dos Santos Franco et al., 2018; Moran, 2016; World Commission on Dams, 2000). The explosive population growth stresses local resources, leaving hospitals, schools, police, and basic sanitation services unable to serve all the incoming population (Grisotti, 2016; Moran, 2016). Unplanned settlements sprout to accommodate the expanding demographic, presenting a challenge to the already limited infrastructure in the Amazon region. This is particularly true of basic sanitation, one of the most regularly observed impacts of dam reservoirs in the Amazon (Tundisi et al., 2003; World Commission on Dams, 2000). The abrupt increase in population brings forth greater water and waste disposal demands. New wells and septic tanks are built by incoming residents to provide for their water and waste disposal needs which results in greater volumes of septic tank contaminants reaching groundwater resources.

### *4.2.2 Impacts of large dams - Basic Sanitation and Water Quality*

Communities hosting large development projects are faced with increased population densities that place severe pressure on their water and sanitation infrastructure (Lerer and Scudder, 1999). In the states of the Brazilian Amazon, provision of basic sanitation services lag behind with 55.4 percent of residents having potable water from a distribution network and only 10.5 percent having sewer services (Ministerio das Cidades, 2018). Under these conditions, residents in the region resort to wells for their water supply and septic tanks for waste disposal. Even the larger capital cities of the Brazilian Amazon rely on the use of septic tanks. These septic tanks generally have an open bottom, allowing liquids to percolate through the soil and reach shallow groundwater resources. Figure 4.1 shows the capital cities located in the Brazilian Amazon and their use of septic tanks.

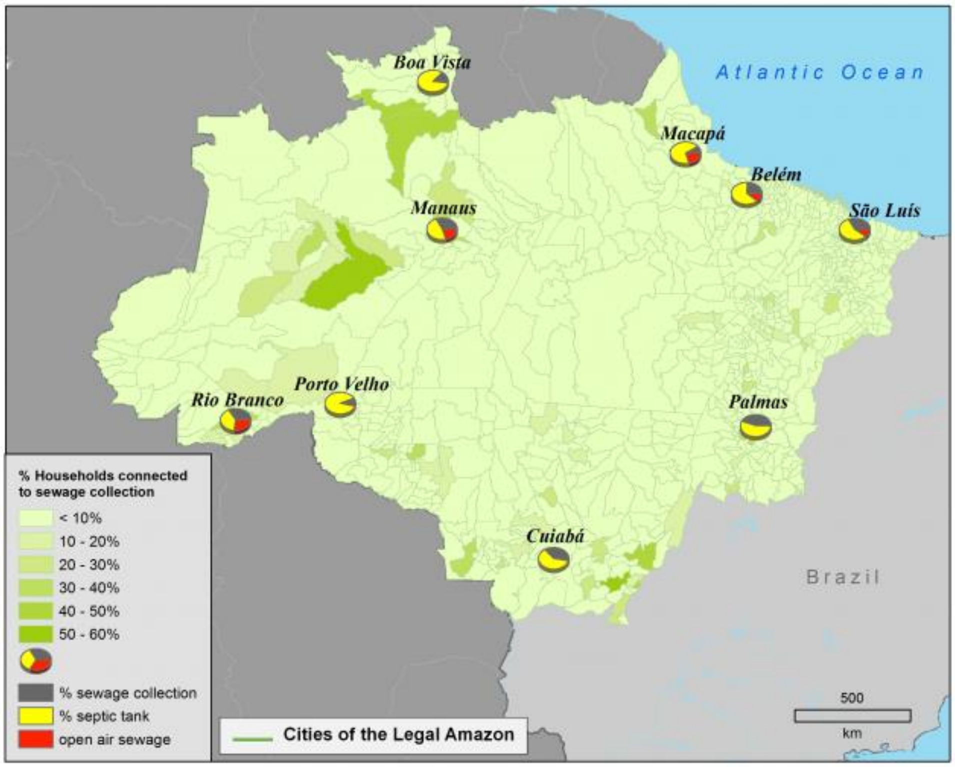


**Figure 4.1**: Proportion of households in Amazonian municipalities and state capitals connected to sewage collection.
*(Brondizio, 2016)*

In the Amazon, large hydroelectric projects are generally hosted in smaller cities that are even less well served than the capital cities shown in Figure 4.1. The significant increase in population and growth of unplanned settlements brings forth greater water demand and waste disposal in these smaller cities. As the population increases, new wells and septic tanks are built and greater volumes of contaminants from septic tanks enter the shallow groundwater resources in the area. Further, distances between new and old structures decrease, reducing contaminant transport times from septic tanks to water wells and putting the health of the population at risk. Watersheds with high septic tanks densities exhibit increased concentrations of fecal indicators and septic systems seem to be the primary driver of increased fecal bacteria levels (Verhougstraete et al., 2015). Further, higher septic system densities are associated with endemic diarrheal illnesses (Borchardt et al., 2003; Hunt et al., 2010), making contaminant transport from septic tanks to water wells a growing concern in the region. Figure 4.2 shows a visual representation of contaminant transport from septic tanks to the aquifer below and, subsequently, to water wells.

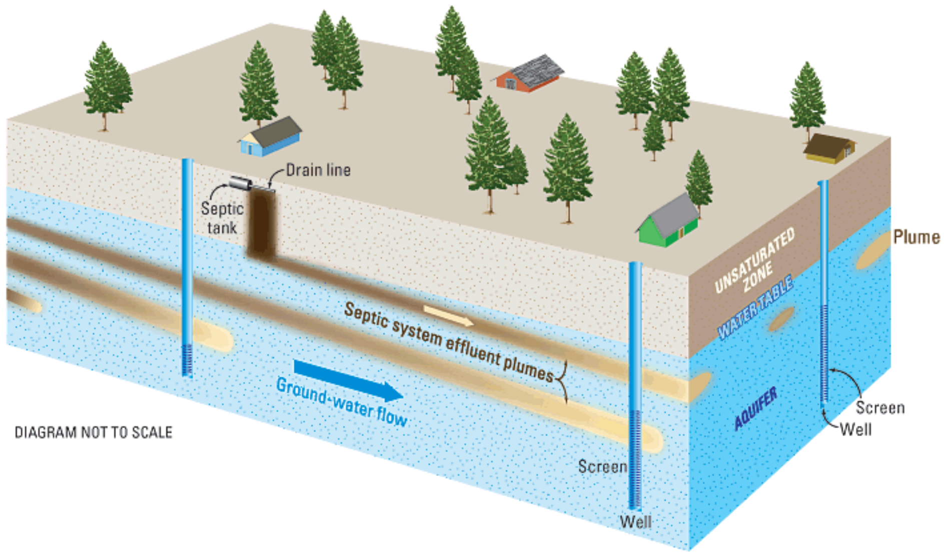


**Figure 4.2:** Contaminant transport from septic tanks to water wells
*(USGS, 2007)*

Areas with a lack of sanitary infrastructure and limited access to clean drinking water are vulnerable to diseases (World Commission on Dams, 2000), making basic sanitation pivotal in the protection of both water resources and human health. However, impacts on sanitation stemming from hydroelectric expansion throughout the Amazon Basin remains an insufficiently examined issue. Thus, the purpose of this paper is to combine multidisciplinary approaches to investigate the interactions that impact basic sanitation and welfare of communities enduring the challenges arising from hydroelectric expansion, not only in the Amazon, but globally. In particular, population density, elevation, and groundwater depth are observed as indicators for potential challenges that need to be addressed prior to the arrival of a dam to any region. Population density is useful in representing the amount of septic tanks in the area and their proximity to neighboring drinking water wells, while household elevation and groundwater depth can uncover information regarding the transport times of contaminants discharged into the aquifer below. The study focuses on general and source tracking fecal contamination markers as water quality indicators. The inclusion of these markers is necessary to potentially associate septic tanks as point sources for fecal contamination to the aquifer below and, subsequently, to water wells in the region. Further, seasonality is taken into account as the vast difference between the dry and rainy seasons in the Amazon may alter contaminant transport and water quality results.

The study draws on geography, biology, and hydrology with the goal of integrating their insight and construct a more comprehensive understanding of sanitation, a topic that is too complex to be understood through the lens of a single discipline. The results of this study can aid in the potential reduction of negative impacts to sanitation emerging from hydropower development. The aim is to contribute to the literature that addresses approaches to ensure availability of water and sanitation for all. Considering sanitation both an important societal and environmental issue that affects water quality, and public health and safety, this project explores the connections between contaminant transport, spatial distribution and geography to potentially avoid future sanitation deficiencies in cities affected by major hydroelectric development projects.

## 4.3 Methodology

### *4.3.1 Site Selection - The Belo Monte Hydroelectric Complex and the city of Altamira*

Located in the State of Pará, along the Xingú River, the Belo Monte Hydroelectric Complex is the largest, most recent project in the Amazon region and was considered the third largest hydropower dam in the world in terms of installed capacity. It is comprised of 24 turbines and 28 dikes, creating a reservoir with a surface area of 478 $km^2$ along the Xingú River (Diniz de Figueiredo, 2015). Construction began in 2011 with inauguration of the 14th turbine occurring in 2019 (Globo G1 Pará, 2019). Diverting 80 percent of the Xingú River's flow towards the turbines, the complex has the potential to generate an average of 11 gigawatts, which will be distributed to 17 Brazilian states, serving approximately 18 million mostly urban residences – an estimated 60 million people served in total.

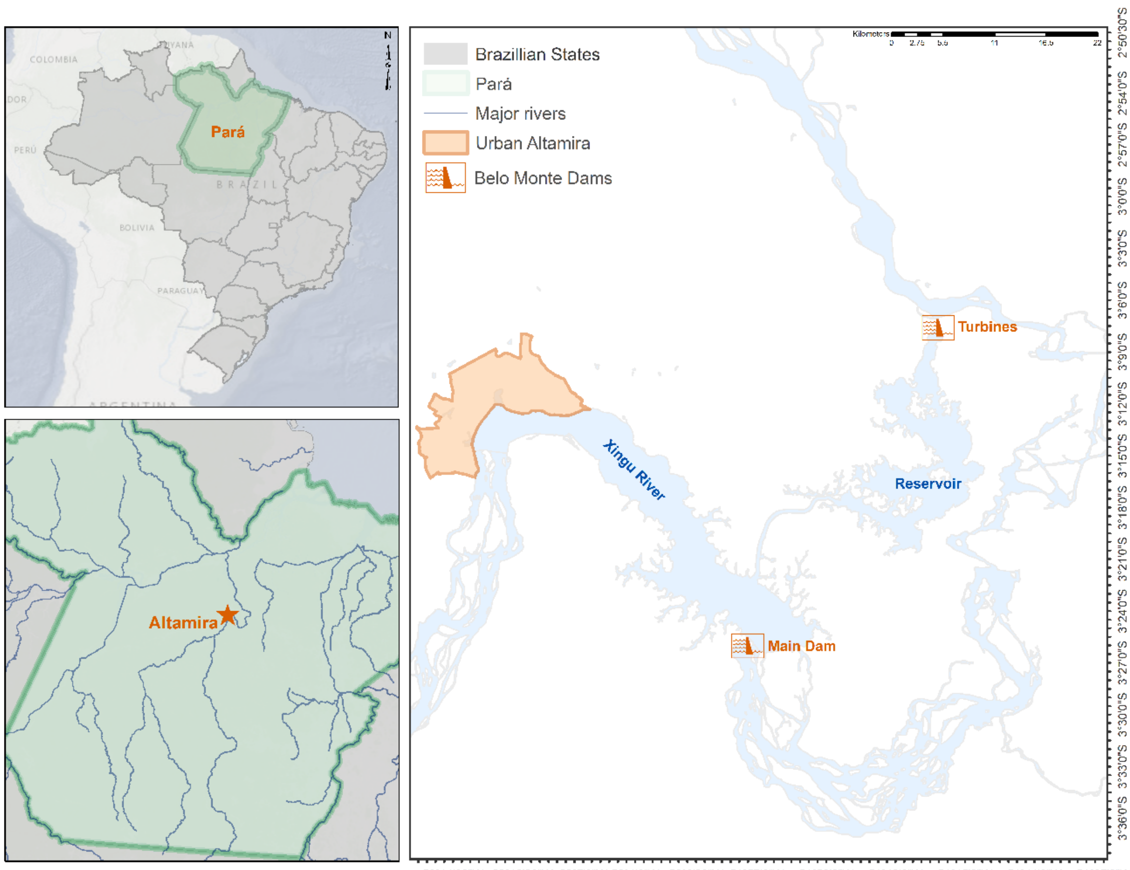


**Figure 4.3:** Study Region

Located 52 kilometers upstream from the main dam, the city of Altamira served as the principal staging area for the construction of the Belo Monte Hydroelectric Complex (Figure 4.3). The construction brought more than 30,000 construction and service sector workers to Altamira, where population rose from 77,439 inhabitants in 2010 to an estimated 109,938 in 2016 (Instituto

Brasileiro de Geografia e Estatística, 2016, 2011a). Nonetheless, people familiar with the area estimate that the actual population may have been closer to 150,000 at the peak of construction, settling back to 110,000 inhabitants towards the end (Marin and Oliveira, 2016; Moran, 2016).

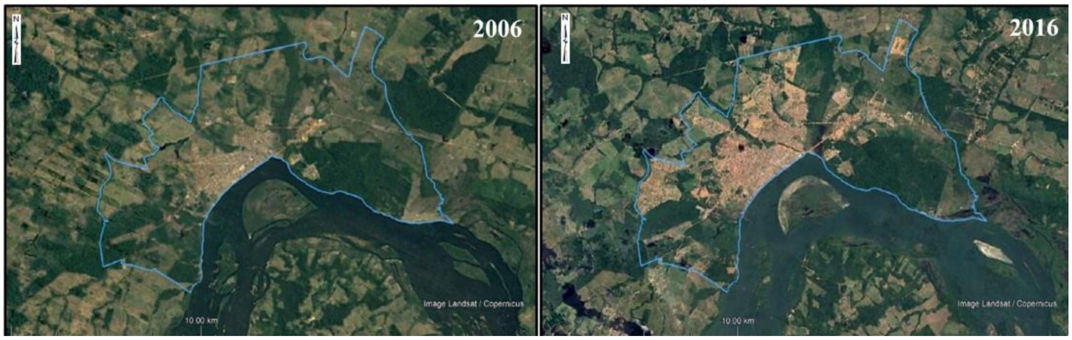


**Figure 4.4:** Urban Growth in Altamira
*(Gauthier and Moran, 2018)*

As previously discussed, population increases brought forth by large construction projects stress basic sanitation in neighboring areas. Altamira was no exception (Figure 4.4). The population increase brought forth by Belo Monte stressed the city's sanitation services. Households lacking connection to the local water distribution system, or receiving an irregular water service, resort to shallow-dug wells. At the same time, not unlike the majority of Amazonian cities, open-bottom septic tanks remain the main wastewater disposal system throughout Altamira (Pessoa, 2016). With the majority of Altamira's urban area feeding off a single unconfined aquifer (CPRM Serviço Hidrogeológico do Brasil, 2014), the increases in septic tank discharges to the ground can lead to contaminants leaching to the aquifer below, ultimately reaching water wells and putting the health of the population at risk (Gauthier et al., 2019; Ministerio Publico Federal, 2016; Pará, 2016; Risebro et al., 2012; Verhougstraete et al., 2015). Further, in Altamira's wet season, rainfall induced infiltration of contaminants can threaten wells as intense rains flood parts of the city, along with low-laying well heads. Consequently, Brazil's Federal Public Ministry deemed the situation in Altamira a critical sanitation crisis (Ministerio Publico Federal, 2017;

Pessoa, 2016).

The disposal practices and sanitation services witnessed in Altamira are similar throughout the Amazon region and in the developing world. If left unexplored, similar sanitation crises will continue to emerge in future hydroelectric development projects in the region. The need to minimize environmental and health issues arising from hydroelectric expansion is crucial as dams continue to play a significant role in sustainable energy portfolios of developing countries. In this sense, Belo Monte and Altamira can serve as a model system for the study of environmental variables impacting basic sanitation and quality of life in communities affected by major hydroelectric development projects. Altamira and Belo Monte will be the focus of the work to explore the link between explosive population growth, basic sanitation, and water quality. Examining elevation, population density, and groundwater depth as indicators for the likelihood of contaminant intrusion from septic tanks to water wells, the study reveals the potential for groundwater contamination in areas upstream of complexes such as Belo Monte.

#### *4.3.2 Sampling Methods*

Thirty household wells located in various elevations and population density areas within urban Altamira were sampled. To determine if human fecal contamination was present in the well, each water sample was analyzed for fecal indicators *Escherichia coli (E. coli)* and *Bacteroides thetaiotaomicron (B.theta).* Groundwater depth in each well was measured through the installation of water level data loggers. Household selection, sampling scheme, and laboratory, and data analyses performed are explained in more detail in the following section. Ultimately, statistical and spatial analyses were performed to determine if there was a significant relationship between elevation, population density, groundwater depth, and presence and magnitude of *E. coli* or *B. theta*. The study also considered seasonality in the sampling, as rainfall induced infiltration of contaminants during the rainy season may have an impact on results.

Historical data from the Brazilian National Metrologic Institute weather station in Altamira reports that from 1981 to 2010, the highest average rainfall occurred during the month of March (414.6 mm) and lowest in August (27.3 mm) (Instituto Nacional de Metereología, 2018). The dry season sampling occurred in late September and early October 2018. The total monthly rainfall for those months was at 68.6 mm and 38.5 mm respectively. Sampling for the rainy season occurred during late February and early March 2019 with total monthly rainfalls of 256.6 mm and 216.6 mm respectively (Instituto Nacional de Metereología, 2019). Although Altamira's rainy season was drier during the year sampled than historical trend averages, a 30 mm per month increase in precipitation between sampled seasons occurred, showing retention of seasonality.

#### *4.3.2.1 Selection of Households*

Households sampled were selected through stratified sampling using elevation and population density as variables. Elevation served as a proxy for potential of rainfall occurring floods or water intrusion to septic systems. Household density served as a proxy for volume of septic contaminants discharged into the aquifer below and shorter transport times between septic tanks and neighboring wells. The same households were sampled during both seasons and all of the wells were covered, but not completely sealed. Sealed wells in Altamira have a cement layer gluing the top in place. Opening the cement seal of household wells for sampling and later reconstructing the seal for them would perturb the routines of participating families. Therefore, unsealed wells were chosen.

##### 4.3.2.1.1 Elevation

Belo Monte's construction involved controlled flooding of low-lying areas upstream of the dam. This included portions of urban Altamira (Norte Energia, 2011) that lay below an elevation of 100 meters above sea level. Using a 30-meter resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM V3) (National Aeronautics and Space Administration Land Processes and Distributed Active Archive Center, 2001) obtained from the NASA Reverb|Echo repository, undefined elevations in the surface raster were filled using the fill tool in ArcGIS software (Environmental Systems Research Institute, 2016; Gauthier et al., 2019). The tool iterates until all sinks in elevation are filled. Areas up to 105 meters above sea level were categorized as low elevation (Figure 4.5) while areas above that threshold were considered high elevation.

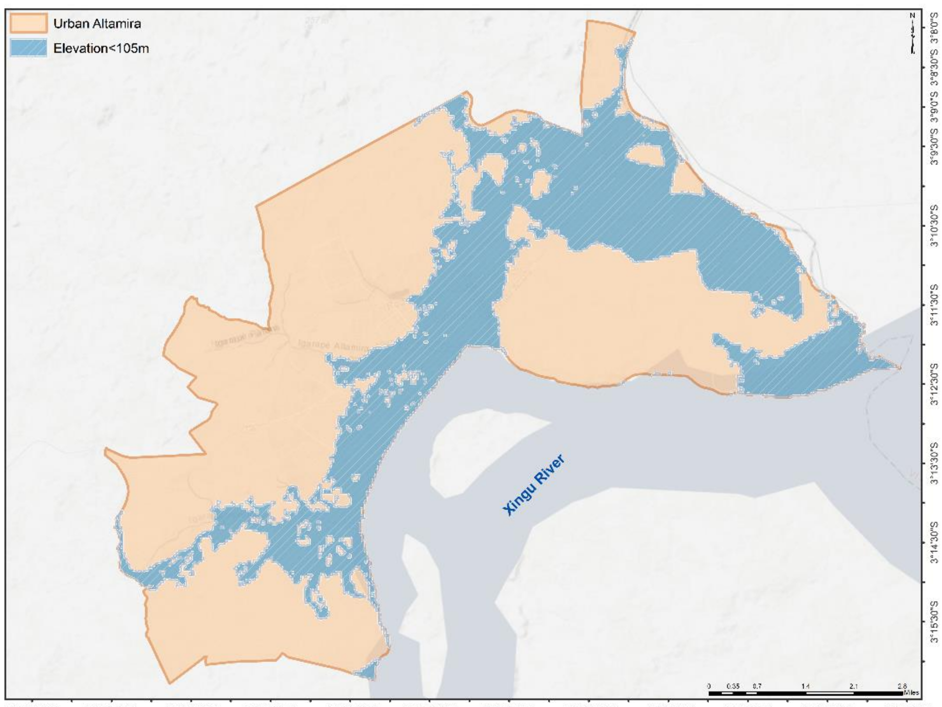


**Figure 4.5**: Areas below 105 meters above sea level in Altamira

4.3.2.1.2 Population Density

Existing classifications of land use and land cover were utilized for the urban area of Altamira. The initial classifications included intense urbanization, sparse urbanization, degraded area, exposed soil, pasture, and forest fragment (Nascimento Costa, 2015). After visual assessment of high-resolution images provided by Google Earth Pro, construction of new urban areas was detected as well as a notable growth of population in existing neighborhoods. The initial classifications were updated to reflect the population growth in the city. Using neighborhood boundaries provided by Altamira's Municipal Secretariat of Planning (SEPLAN), ArcGIS software was used to calculate area by neighborhood (Environmental Systems Research Institute, 2016). Houses per square kilometer were calculated in each neighborhood with the use of IBGE population by neighborhood data (Sistema de Recuperação Automática, 2010).

The 100-meter flood line used to displace the population for the Belo Monte construction was superimposed, allowing for the measurement of area reduction in each neighborhood. Portions of the neighborhoods that were previously populated and subsequently flooded after the construction of Belo Monte were identified through visual corroboration and the new neighborhoods that were built for the displaced families at higher elevations were corroborated. This analysis allowed for an approximation of the shifts in population for each neighborhood. With this data, the population in each neighborhood was recalculated based on the percentage of population lost or gained after the reservoir-induced flooding. The city was then reclassified into high, medium, and low population density areas. Employing the natural breaks classification method and visual corroboration, sparse urbanization was determined as having low population density with 10 to 100 homes per square kilometer, moderate as having a medium density with 135 to 800 homes per square kilometer, and intense urbanization as having a high population density with 895 homes per square kilometer or more.

An analysis of elevation and population density yielded a stratified sample of 6 groups as depicted in Figure 4.6. Initially, five household wells would be sampled from each group. Unfortunately, this yielded homes that were too close together, less than 250 meters apart. This would produce no new information in regards to groundwater depth between households. Hence, to attain a more spatially distributed sample, two households were rearranged into the low density-high elevation category. The same household wells were sampled in both the dry and rainy seasons. Households sampled, along with population densities, are observed in Figure 4.7.

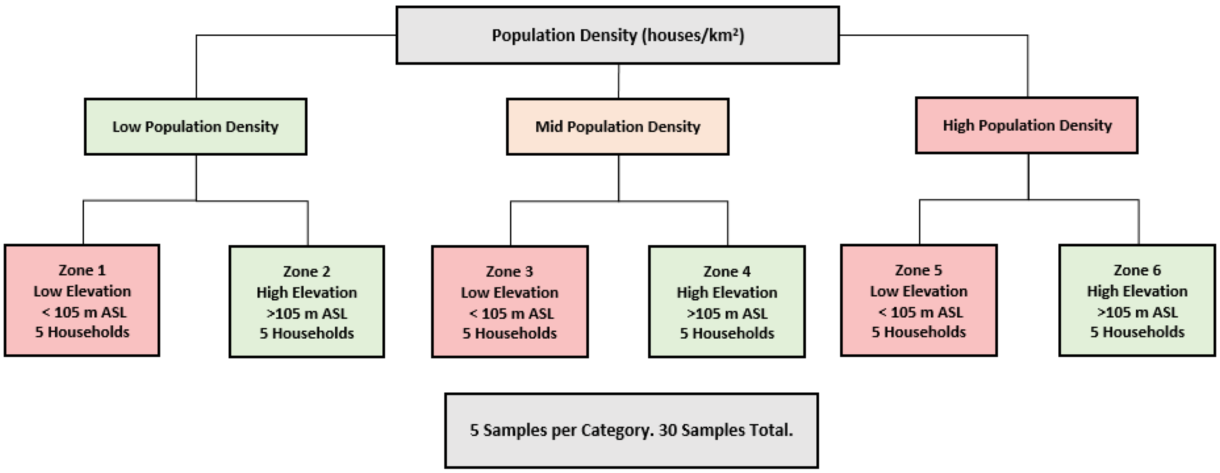


**Figure 4.6:** Groups resulting from the stratified sampling of households.

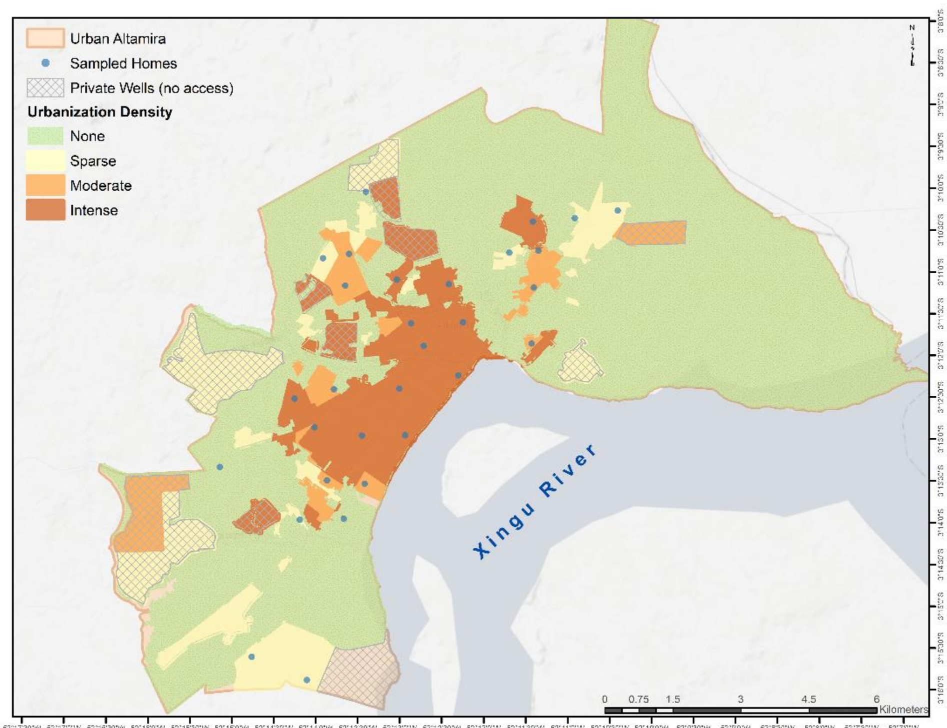


**Figure 4.7:** Urbanization density and households sampled.

#### ***4.3.2.2*** *Groundwater Level Monitoring*

Continuous data collection of groundwater levels was performed from September 2018 through May 2019 using *Solinst3001 LT Junior Edge Leveloggers*. These loggers measure total (absolute) pressure and, when submerged, they record the combination of barometric pressure and water pressure. These measurements are then used to determine the groundwater levels in each well. Loggers were installed in households whose wells did not have a sealed cap in order to accommodate for easier installation, monitoring, and recovery of equipment. Data storage capacity allowed each logger to collect data at 6-minute intervals. Upon installation, the distances to the water surface and to the bottom of each well were measured using an electric tape. Loggers were placed up to one meter below the water level in each sampled household. Location data and depth of installation was also recorded for each logger. A Garmin eTrex 20 Global Positioning System was used for initial location data and further corroboration of coordinates and elevation was performed using Google Earth Pro software. Loggers underwent on-site inspection in March 2019, when they were connected to a computer with an Optical Reader Cable to transfer information collected. They were immediately re-installed. Residents informed any extraordinary activities that may have caused unusual readings such as pump repairs or well maintenance. Removal of loggers occurred in May 2019.

#### ***4.3.2.3*** *Fecal indicators*

##### 4.3.2.3.1 Escherichia coli

*Escherichia coli (E. coli)* is the main freshwater fecal indicator bacteria used by regulatory agencies and international health organizations to determine groundwater quality and has long been accepted as a marker of fecal contamination (Ashbolt et al., 2001; Edberg et al., 2000; Ferguson et al., 2012; Odonkor and Ampofo, 2013; Rochelle-Newall et al., 2015). *Aquagenxx's*

*Compartamental Bag Test (CBT) kit* (Chapel Hill, North Carolina) was used for the samples analyzed, as it provides a clear, quantitative assessment for *E. coli* presence and magnitude. CBT allows for quick, inexpensive water quality monitoring and is a practical optimized field test for low resource or difficult sampling areas such as Altamira's household wells. It is a most probable number (MPN) chromogenic method for rapid detection and quantification of *E. coli* in drinking water.

One liter of water was extracted by lowering a sterile bottle directly into each well. A bottle of distilled water of the same volume was used as a field blank to account for method integrity. All bottles were stored in a cooler at 4°C for less than 4 hours at a time and transported to a partner laboratory for *E. coli* testing and further filtration through membranes. Once at the laboratory, 100 milliliters (ml) of each sample were transferred to sterile bags and mixed with chromogenic culture media. Once fully mixed, the sample was transferred into the CBT and distributed into five compartments with volumes of 1 ml, 3 ml, 10 ml, 30 ml and 56 ml. The bags were sealed and left to incubate for 24 hours at a temperature of 42°C. After incubation, a blue color indicated presence of *E. coli* while a yellow color indicated absence. A water quality rating chart, provided in the CBT kit, was used to assess MPN per 100 ml in each sample showing presence of *E.coli*. Upon completion, bags were decontaminated with chlorine tablets for 30 minutes. The volume was disposed in a toilet and the bag was placed in the trash.

One of the limitations of using traditional fecal indicator bacteria such as *E. coli* is that the origin of contamination cannot be determined. *E. coli* can be frequently found in tropical soils and in the feces of most warm blooded animals (Byappanahalli et al., 2012; Farnleitner et al., 2010; Franz et al., 2008; Naganandhini et al., 2015; Ongeng et al., 2011; Zhang et al., 2013). The presence of *E.coli* in wells can stem from various forms of contamination intrusion, including aboveground sources. Therefore, the inclusion of human specific markers is necessary to potentially associate septic tanks as point sources for fecal contamination to wells in Altamira. *Bacteroides thetaiotaomicron* (*B.theta*), a highly human-specific fecal pollution marker (Aslan and Rose, 2013) was chosen as the human specific marker for this study.

4.3.2.3.2 Bacteroides thetaiotaomicron

In order to identify sources of contamination in the wells, microbial source tracking (MST) techniques and quantitative Polymerase Chain Reaction (qPCR) assays were used. MST is a field within environmental microbiology that has grown to develop useful technologies in the prediction of sources of fecal pollution (Scott et al., 2002). Most MST methods can utilize genetic markers and qPCR for fecal pollution source detection. In the qPCR is a laboratory technique, a DNA sequence is amplified for real-time detection and quantification of a particular DNA molecule.

Host specific *Bacteroides* genetic markers have long been used to detect human fecal pollution (Ahmed et al., 2012, 2009, 2008; Aslan and Rose, 2013; Mayer et al., 2018; Pierre et al., 2017; Reischer et al., 2013; Scott et al., 2002; Verhougstraete et al., 2015; Weiss et al., 2016; Yampara-Iquise et al., 2008).Particularly, the *Bacteroides thetaiotaomicron* (*B.Theta*) α-1–6 mannanase gene has a high human specificity. We performed analysis of our water samples using qPCR assays targeting this gene (Aslan and Rose, 2013; Yampara-Iquise et al., 2008). Using a sterile autoclaved funnel for each water sample 150 ml of every water sample was vacuum filtered through a polycarbonate membrane (47 mm, 0.45µm pore size). A distilled water filtration blank was also filtered for each day of sampling. Two additional replicates were filtered for every sample and filtration blank. Using sterilized forceps, the filters were folded with contents facing inward, placed in a previously autoclaved 2ml micro centrifuge tube, and frozen at -20°C. After processing all samples, membrane filters were transferred to a cooler with icepacks and transported to a collaborating laboratory for DNA extraction and analysis.

The DNEASY® PowerWater Kit (QIAGEN Group) was used for DNA extraction. The manufacturer's instructions were followed to prepare the DNA for the qPCR process. qPCR was performed on extracted DNA using an Applied Biosystems™ QuantStudio™ 3 Real-Time PCR System. The primers amplified a 63-bp product with forward primer 4515901F (sequence 5'CATCGTTCGTCAGCAGTAACA'3), and reverse primer 4515963R (sequence 5'CCAAGAAAAAGGGACAGTGG'3). The probe used was Probe 62 (sequence 5'FAM-ACCTGCTG-NFQ'3) from the Roche Universal Probe Library. Serial dilutions of genomic DNA (ATCC 29148-5) were prepared and used for standard curve development. The qPCR amplification reaction mixture contained 10 μL of Applied Biosystems® TaqMan® Environmental Master Mix 2.0, 0.4 μL forward and reverse primers, 0.2 μL Probe 62, 4.0 μL nuclease-free water, and 5.0 μL of extracted DNA and processed in triplicate. The thermal cycling included a 15-min, 95 °C pre-incubation cycle, followed by 50 amplification cycles, and a 0.5-min 40 °C cooling cycle. The detection limit of the assay was 10 copies 5 $\mu l^{-1}$. Molecular-grade water was used for negative controls during each qPCR run. Statistical analyses for results, including regressions, were performed using R and STATA software while spatial analyses for all location data were completed in ArcGIS Desktop.

## 4.4 Results and Discussion

### *4.4.1 E.coli and B.theta*

During the dry season, 19 of 30 homes sampled tested positive for *E. coli* with concentrations ranging from 1.1 to greater than 100 MPN/100mL and geometric mean of 10.13 MPN/100mL. Samples with no contaminant detection were excluded from the calculation. Thirteen homes tested positive for *B. theta* ranging from 37.02 to 43460.58 copies/mL and a geometric mean of 4132.69 copies/mL. Eight of the homes tested positive for both markers. In the wet season 23 of 30 wells had *E.coli* present with concentrations ranging from 1.0 to greater than 100 MPN/100mL and geometric mean of 7.88 MPN/100mL. Eleven homes tested positive for *B. theta* ranging from 352.65 to 13844.95 copies/mL and geometric mean of 4873.45 copies/mL. Ten homes tested positive for both markers during the rainy season.

Seven homes which had previously tested negative for *E.coli* in the dry season, tested positive in the wet season. Only two homes exhibited the opposite. Fourteen homes had an increased concentration of *E.coli* in the wet season, and eleven homes showed an increased concentration of *E.coli* in the dry season. Only five households exhibited no changes in *E.coli* presence or concentration between the seasons.

During the dry season, presence of *E. coli* was observed in 63 percent (±17.2 percent at a 95% confidence) of the households in our sample, demonstrating the existence of fecal contaminants in the local groundwater resources. *B.theta* was found in 43 percent (±17.7 percent at a 95% confidence) of the households samples, indicating human fecal contamination in the local groundwater resources. The wet season exhibited presence of *E.coli* in 76 percent (±15.1 percent at a 95% confidence) of the households sampled and *B.theta* was found in 37 percent (±17.2 percent at a 95% confidence) of the households.

The increase in the number of homes with presence of *E.coli* during the wet season may suggest that this contaminant has a greater spatial reach during that season. Due to the small sample size, the increase was not statistically significant. *B.theta* was found in less households and in less concentrations during the wet season.

### *4.4.2 Groundwater Depth*

***4.4.2.1*** *Groundwater Depth and Household Elevation*

A Spearman rank correlation test was performed using R software (R Development Core Team, 2008) to determine the impact of household elevation on depth to groundwater measurements. A statistically significant positive correlation between the elevation of the households and depth to groundwater was found in both the dry (S = 720.38, p-value = 6.587e-09, rho = 0.8397378) and wet (S = 521.79, p-value = 4.044e-08, rho = 0.8407225) seasons. Depth to groundwater was greater in households located at higher elevations (see Figure A.1 of the Appendix section). This, along with proximity to the Xingu river, indicates that the water table maintains a fairly consistent elevation throughout the alluvial aquifer. Given that these variables are highly correlated, and to avoid multicolinearity, groundwater depth was maintained as a variable while household elevation was eliminated from analyses. We determined the elevation of the water table at each sampled location by subtracting groundwater depth from surface elevation.

As expected with heavy rains, groundwater levels rose in the wet season in all except two of the homes. The rise in groundwater levels ranged between 1.70 meters to 0.13 meters. Groundwater levels showed a significant decrease towards the end of November and were at their highest during the month of May. There was no statistically significant correlation observed between the elevation of the wells and the change in groundwater levels (S = 3713.2, p-value = 0.5069, rho = -0.133466).

***4.4.2.2*** *Groundwater Depth, Contaminant Presence, and Contaminant Concentrations*

A One Way ANOVA and a Mann Whitney U test both revealed no statistically significant relationship between the groundwater depth (numerical variable) and the presence of contaminants (categorical variable) in sampled wells. Figures A.2 and A.3 of the Appendix section show that contaminants were found in wells at varying groundwater elevations. Further, a statistically significant moderate positive correlation was found between groundwater depth and *E.coli* concentrations in the dry season (S = 2596.5, p-value = 0.02007, rho = 0.4223499). As previously stated, a greater number of homes tested positive for *E.coli* during that season which makes for an expected correlation. A statistically significant moderate negative correlation was also found between the change in groundwater levels and *B.theta* concentrations in the wet season (S = 4660.2, p = 0.02812, rho = -0.4225253). Table A.1 of the Appendix summarizes correlation results. Due to the small comparative datasets, establishing *B. theta* reference conditions for Altamira would require additional sample analysis and a greater understanding of the bacterial distributions.

Bivariate Generalized Linear Regression models showed no association between groundwater depth and contaminant presence but did find a statistical significance between *E.coli* concentrations and groundwater depth in the dry season (Appendix section Tables A.2 and A.3). However, in order to better visualize groundwater depth and its relationship with contaminant magnitudes, kriging was performed on the groundwater levels measured at the time water samples were taken. Kriging is a method of interpolation for which values are modeled by a Gaussian process. Under suitable assumptions, kriging gives the best linear unbiased prediction of the intermediate values between sampled points. Although kriging is most appropriate with a larger dataset, it allows for basic exploration of the water table.

The Jenks Natural Breaks Classification was used for the groundwater levels on ArcGIS. *E.coli* concentrations were categorized in accordance with the World Health Organization's Guidelines for Drinking Water Quality (World Health Organization, 2011) as follows: 0/100 mL = Safe; 1-10/100 mL = Intermediate Risk; 11-100/100 mL = High Risk; and >100/100 mL= Very High Risk. While there is no such guideline for *B.theta* concentrations, seasonal results were divided into quantiles in ArcGIS and assigned a zero value in the locations where no contaminant was detected, these were regarded as 'Safe'. Figure 4.8 – 4.11 show the concentration of contaminants for both seasons where, as observed, differing contaminant concentrations were found throughout varying groundwater depths. *E.coli* shows a clear increase during the wet season, most evidently in areas with shallower groundwater depth. Contaminant concentration data was transformed to a logarithmic scale and regressed with groundwater levels which further confirmed that groundwater level bears significance on *E. coli* concentrations during the dry season. Figure A.4 in the Appendix section depicts contaminant concentration transformations while Table A.4 shows regression results.

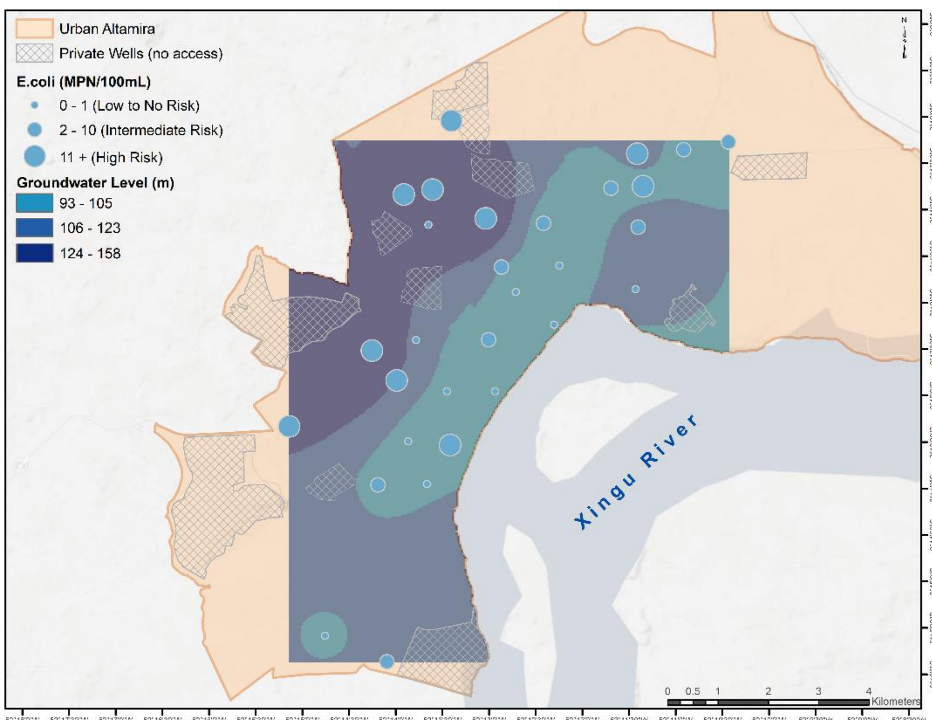


**Figure 4.8**: Concentration of *E.coli* and groundwater levels during the dry season.

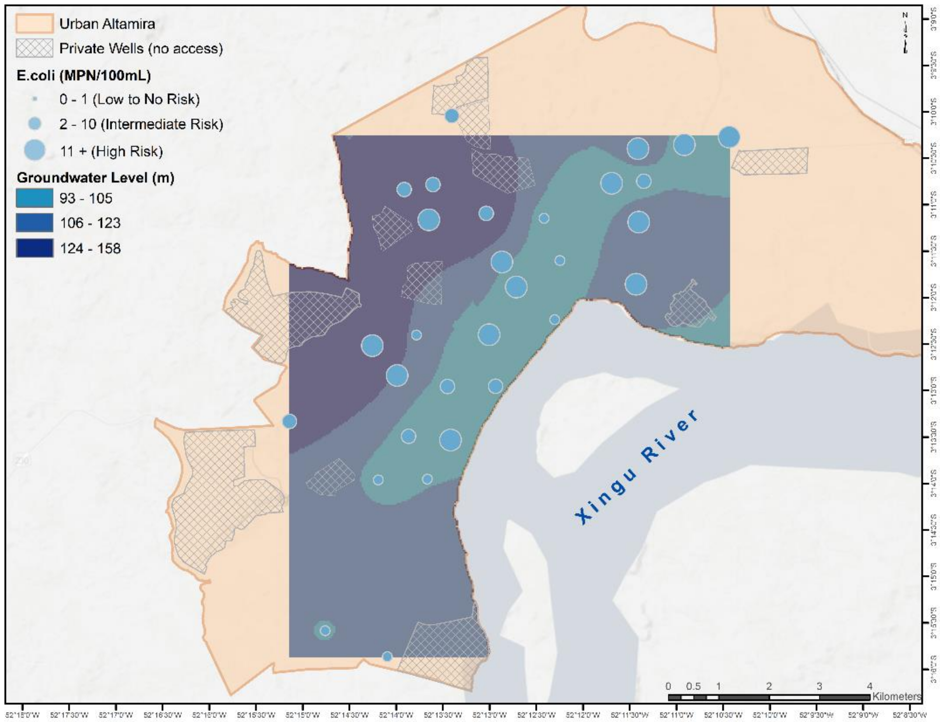


**Figure 4.9**: Concentration of *E.coli* and groundwater levels during the wet season.

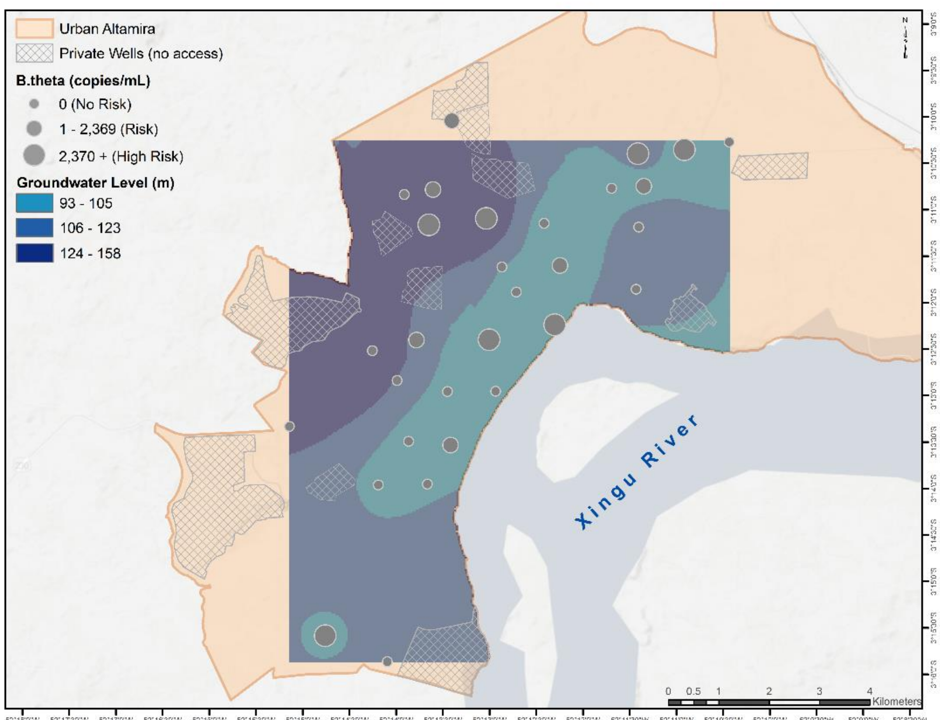


**Figure 4.10**: Concentration of *B.theta* and groundwater levels during the dry season.

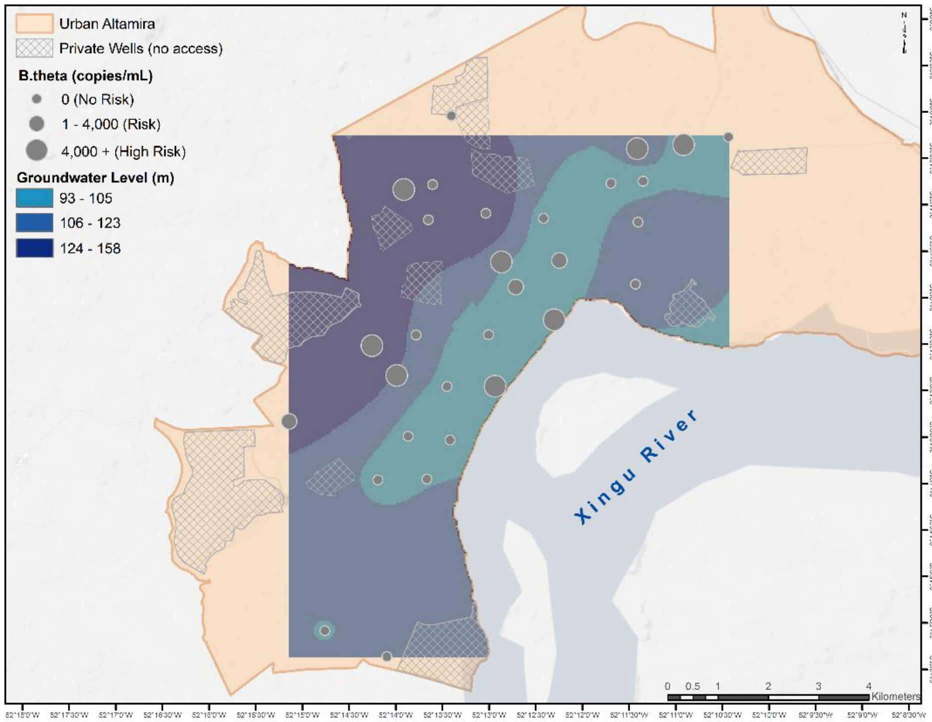


**Figure 4.11**: Concentration of *B.theta* and groundwater levels during the wet season.

A more detailed assessment of the groundwater dynamics in the region was pursued through groundwater modelling, which provides a better understanding of contaminant transport and groundwater behavior within the city. Groundwater modelling for the stream network surrounding Altamira was attempted repeatedly using *Aquaveo's* Groundwater Modelling Software and publicly available soil and groundwater data from the Brazilian Geological Service and Ministry of the Environment. However, groundwater modelling efforts proved unsuccessful and results differed greatly from ground truth points collected in the field. After numerous attempts, it was omitted from the scope of this study.

### *4.4.3 Population Density*

#### ***4.4.3.1*** *Population Density, Contaminant Presence, and Contaminant Concentration*

Due to the lack of zoning during Altamira's early development and subsequent expansion, population density does not necessarily reveal a particular structure indicative of a social level.

Social classes within and between neighborhoods in urban Altamira are mixed in nature. Belo Monte's arrival further obfuscated any potential distinction. As new residences were built for the incoming population, certain areas were constructed for white collar workers such as engineers and technicians to purchase. However, the housing market did not develop as expected and those same residences were later taken and occupied over by a lower social class than initially intended. Further, with Belo Monte's arrival, the cost of rental properties and general cost of living in urban Altamira soared. Resettlement communities built for displaced families of a lower social level were in some cases sold by residents to incoming migrants at a greater price. Hence, the social complexities of the city are not reflected by the population density of its neighborhoods. Issues of social class and exposure to contaminants are explored in a subsequent study.

While population density may not provide information on social class, it provides information regarding the potential risk of water quality degradation and presence of contaminants in densely populated areas of urban Altamira. During the years sampled, the majority of homes in Altamira had septic tanks. Hence, it is hypothesized that areas with higher population density are also areas with a higher concentration of septic systems. These regions may exhibit a higher presence of contaminants and, perhaps, a greater concentration of contaminants due to the decreased transport times between septic systems and water wells. A Pearson Chi Squared Test was performed between population density and presence of contaminants. A statistically significant relationship was found between population density and *B. theta* presence in the wet season (X-squared = 9.9043, df = 2, p-value = 0.007068). Closer inspection of that season showed statistical significance for both the medium (X-squared = 5.7476, df = 1, p-value = 0.01651) and high density population areas (X-squared = 5.3589, df = 1, p-value = 0.02062) and the presence of *B.theta*. This supports the hypothesis that the densest populated areas in the city show a higher presence of the human marker during the wet season, when rains may spread contaminant transport.

Figures 12-15 show the concentration of fecal contaminants in relation to population density for both the dry and wet seasons. The increase in *E.coli* during the wet seasons is observed in areas of differing urbanization density. However, *B. theta* concentrations during the wet season occurred mostly in the densest populated areas of Altamira. Regressions were performed to determine the effect of population density on contaminant presence and concentrations (Tables A.5 and A.6 in the Appendix section). Significance was found between medium and high population density and *B.theta* concentrations in the dry season. Multivariate regressions were performed on *E.coli* and *B.theta* concentrations for both the dry and wet seasons using Population Density categories (Low, Mid, High) and Groundwater Levels for the corresponding seasons. No deviations from previous results were found, multivariate regressions revealed significance of groundwater levels on *E.coli* concentrations for the dry season in all population density categories (p-value = 0.00135) as well as significance of medium and high population densities on *B.theta* concentrations in the dry season (p-value = 0.00576).

While groundwater level and population density can be used as initial indicators for evaluating potential presence of contaminants in wells, many other variables can contribute. In order to look for further associations, multivariate regressions were performed on *E.coli* and *B.theta* concentrations for both the dry and wet seasons using household water use per day, well distance from septic system, groundwater levels, and population density as independent variables. Interaction terms between septic distances and population density were included, as the densest neighborhoods tend to have closer distances between homes. As previously discussed, regression results confirmed groundwater level significance on *E.coli* concentrations in the dry season regardless of population density (p-value = 0.00135). Moreover, distance from a households well to their septic system presented statistical significance in areas of medium and high population density for *B.theta* in the dry season (p-value = 0.00576). It is worth noting that distance from well to septic tank was only measured within the household interviewed and neighboring septic systems, which may present shorter distances, were inaccessible and, thus, not measured. Further analysis of potential contributing variables was excluded from the scope of this study.

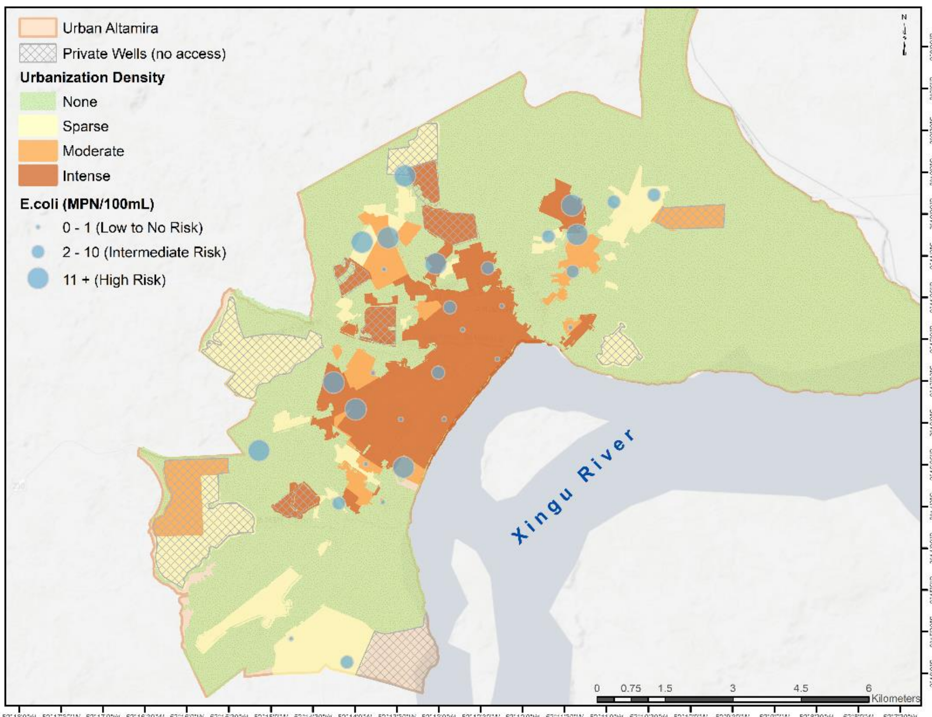


**Figure 4.12:** Concentrations of *E.coli* in varying population density areas during the dry season

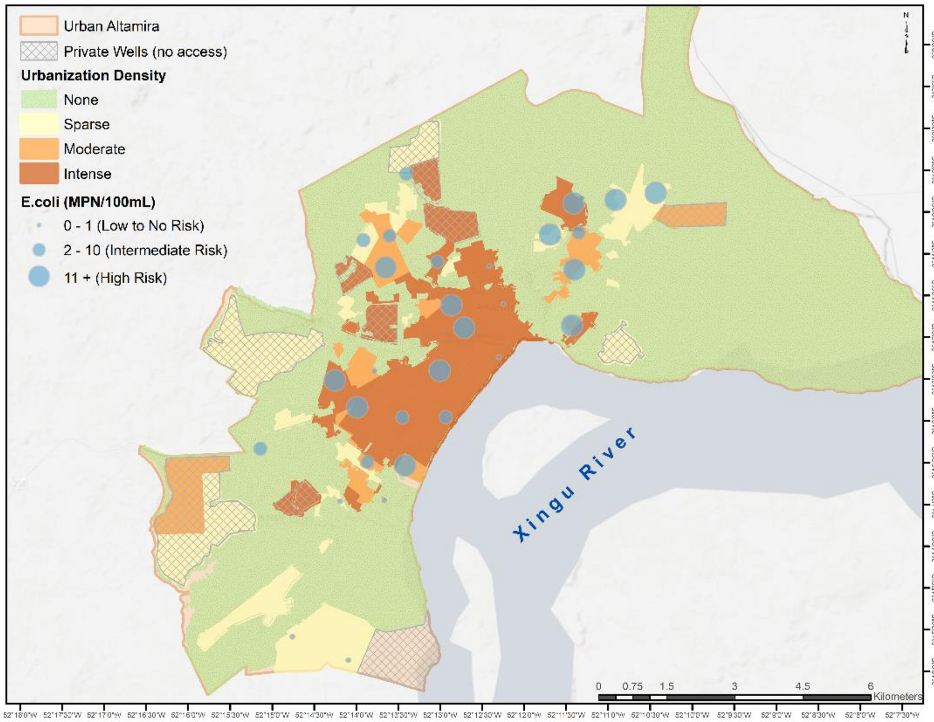


**Figure 4.13**: Concentrations of *E.coli* in varying population density areas during the wet season

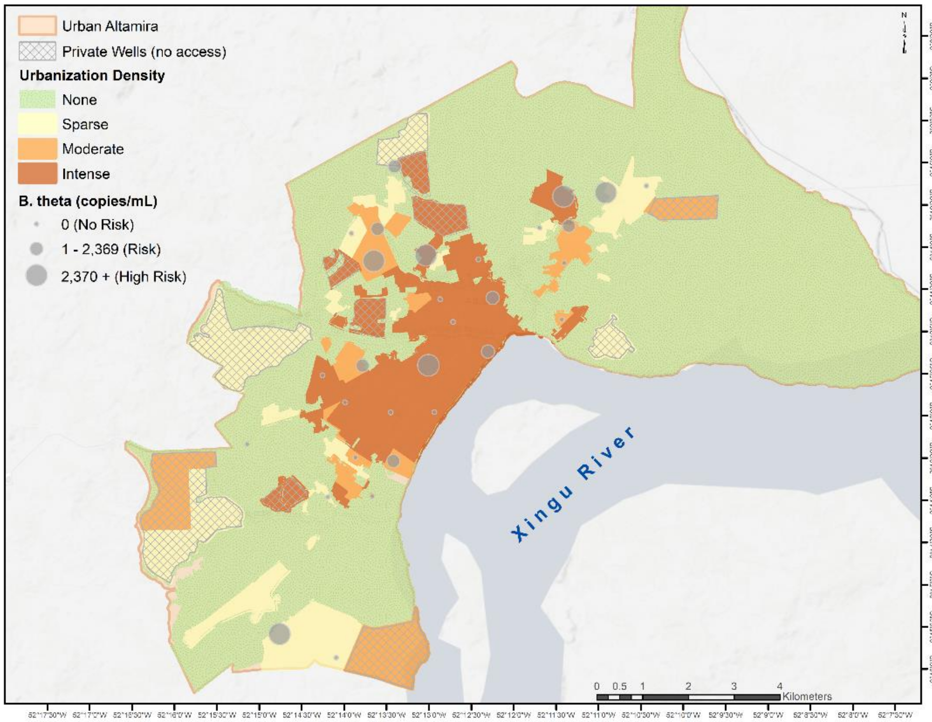


**Figure 4.14**: Concentrations of *B.theta* in varying population density areas during the dry season

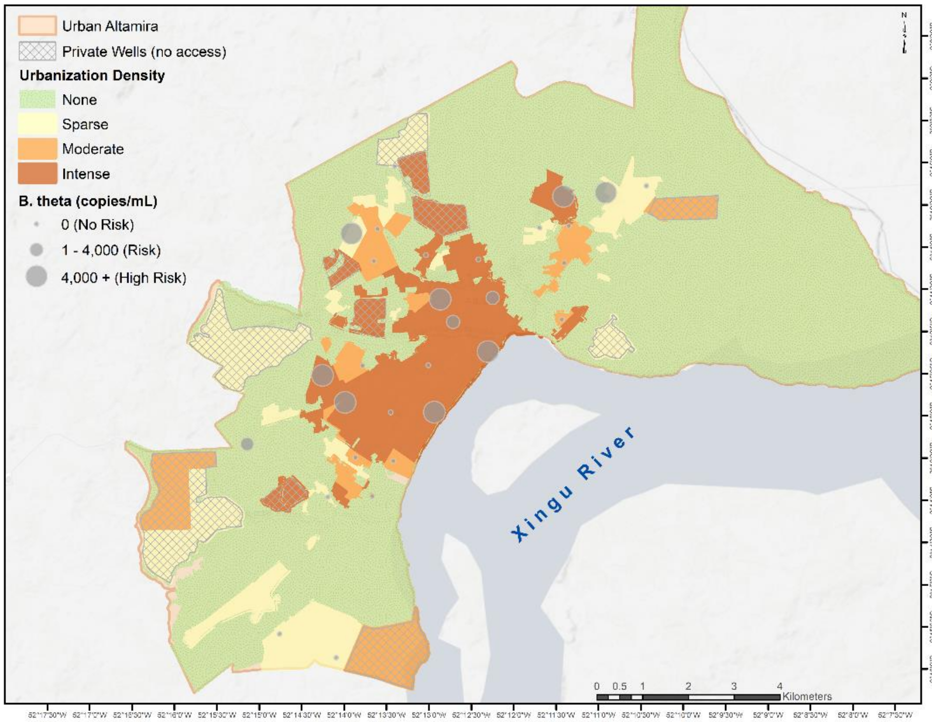


**Figure 4.15**: Concentrations of *B.theta* varying population density areas during the wet season

## 4.5 Conclusion

Altamira's groundwater resources show the existence of fecal contaminants and evidence of human fecal contamination in residential drinking water wells within the city. Although during the sampled year Altamira's rainy season was drier than in historical trend averages, a 30 mm per month precipitation increase occurred between seasons. Seasonality was reflected in the rise of groundwater levels within the city and, as expected, this affected the reach and concentration of contaminants. This is illustrated by the increase of homes testing positive for *E.coli* during the wet season. *E.coli* was found in less homes but at higher concentrations in the dry season and in more homes at a lower concentration in the wet season, when heavy rains result in contaminant dilution. The seasonal change of groundwater levels in the city revealed a positive correlation between groundwater depth and *E.coli* concentrations in the dry season but not in the wet season. This contaminant had a greater spatial reach, yet a lesser concentration, during the wet season.

Moreover, *B.theta* was found in less households during the wet season perhaps due to a dilution of the contaminant below a detectable limit. This is supported by the negative correlation found between the change in groundwater levels and *B.theta* concentrations in the wet season. It is worth mentioning that, due to the small sample size, the increases in the number of households showing presence of contaminants was not statistically significant and a more extensive sampling is required to expand on these findings. Also, due to the small comparative datasets of this study, establishing *B. theta* reference conditions for Altamira would require additional sample analysis and a greater understanding of the bacterial distributions. Further studies are required to expand and strengthen findings.

Concentrations were transformed to a logarithmic scale and their linear regressions confirmed that groundwater depth bore significance for magnitude of *E.coli* in the dry season Appendix Table A.4). Kriging analyses confirmed that the increase of *E.coli* observed during the wet season occurred most evidently in areas with shallower groundwater depth. However, groundwater depth was not the sole indicator of potential risk for contaminant presence and magnitude in wells. Population density was also correlated to contaminant presence and concentrations. Particularly, a significant relationship was found between population density and *B.theta* presence in the wet season. *B. theta* concentrations occurred mostly in the densest populated areas of Altamira. Medium and high population density areas showed statistically significant relationships to *B.theta* concentrations within the sampled homes. It is worth noting that, while seasonality, groundwater depth, and population density all were useful initial indicators for evaluating contaminant presence and magnitude, it is imperative that future work integrates groundwater modelling and a larger sample to better assess fecal contaminant transport within the city.

Identifying the areas and seasons where there are increases in fecal contaminants can aid in the reduction of negative impacts to groundwater resources emerging from the population boom brought forth by large hydropower development projects. This knowledge is crucial in developing strategies to tackle sanitation in areas that are most vulnerable to cross contamination from septic tanks to drinking water wells and yields a more comprehensive understanding of where efforts should be focused to ensure availability of water and sanitation for all. In the case of Altamira, both groundwater level and population density showed statistical significance in the presence and concentration of contaminants within residential drinking water wells. Nonetheless, socioeconomic variables play in important role in a household's access to adequate water and sanitation services and further studies should address additional contributing variables of a social nature in order to better understand risk within Altamira's population.

Sanitation and health challenges need to be addressed prior to the arrival of a dam to avoid future sanitation deficiencies in cities affected by major hydroelectric development projects. The abrupt population increase brought forth by such large development projects generates larger water and waste disposal demands which results in greater volumes of contaminants reaching groundwater resources and, subsequently, drinking water wells. This makes the impact of the current expanding Amazonian demographic on basic sanitation of great importance. Understanding the connections between social and environmental variables such as population density, contaminant magnitude, and its spatial distribution is imperative to avoid sanitation deficiencies in cities affected by major hydroelectric development projects. Improving the sanitation systems in place and increasing the portion of the population served with adequate and safely managed services remains a goal yet to be attained in the case of Altamira and the Belo Monte project.

Appropriate sanitation is both a societal and environmental issue that affects water quality and public health. The information provided in this study aims to improve understanding of the connections between social and environmental variables to potentially prevent or at the very least lessen future threats to water quality in regions where large development projects will be implemented. The information provided can aid in the development of approaches that ensure availability of water and sanitation for all, contributing to literature that addresses the necessity for the expansion of adequate and equitable access to safe drinking water globally.[5]

[5] This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (DGE1424871). Partial funding was provided by the Department of Geography, Environment, and Spatial Sciences, the Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP, processo 2012/51465-0), and the Tinker Foundation through the Michigan State University (MSU) Center for Latin American and Caribbean Studies. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or that of the other funding sources cited above. Funding agencies had no involvement in the study design; collection, analysis and interpretation of data; in the writing of the report; nor in the decision to submit the article for publication. The authors thank the participants surveyed and officials interviewed. Additional acknowledgements to faculty at MSU Department of Geography, the Institute of Biology at University of Campinas, and the University of Pará (Altamira campus). Specifically, Dr. Da Silva Leite, Dr. Raírys Cravo Herrera, Dr. Miquéias Calvi, Luiza Petri, Delziane Araújo, Evelyn Shimon, Taila Alves and Daniel Teixeira for their tremendous help and assistance on and off the field. Particular thanks to Dr. Emilio Moran, Dr. David Hyndman, Dr. Joan Rose, and Dr. Joseph Messina for their ongoing guidance.

**THE SIGNIFICANCE OF SOCIOECONOMIC LEVEL ON THE EXPOSURE OF HOUSEHOLDS TO FECAL CONTAMINANTS AND ON PREVENTION OF CONTAMINANT INGESTION.**

## 5.1 Abstract

Communities hosting large development projects are suddenly faced with increased population densities which place severe pressure on their infrastructure, particularly in water and sanitation. In the states of the Brazilian Amazon, only 55.4 percent of residents have potable water from a distribution network and only 10.5 percent have sewer services. Under these conditions, residents resort to water wells for their water supply and septic tanks for waste disposal which can create cross contamination. Using surveys and water quality results from thirty household wells in Altamira, Pará, this paper examines the significance of socioeconomic level as a variable in exposure to contaminants from septic tanks to water wells as well as contaminant ingestion. Results showed limitations in water access, particularly in lower socioeconomic level homes located in high elevations. Lower socioeconomic homes also presented less connections to sewer services. The presence of contaminants in wells was not related to socioeconomic level, yet lower concentrations of one fecal contaminant were observed in higher socioeconomic level homes. A relationship was also observed between socioeconomic level and water treatment with higher socioeconomic homes purchasing or filtering their drinking water more than their counterparts. Boiling and chlorination were low cost appropriate ways used to avoid contaminant ingestion. Water access and quality was found to be more readily available for higher socioeconomic level homes which had sewage services and water treatment systems. The role of water and contaminants as a pathway for illness in low socioeconomic populations needs to be further examined in Altamira. Social and environmental components need to be examined together in order to provide a more accurate picture of the full impacts of large dam developments. Integrating multiple insights to construct a more comprehensive understanding of the problems faced in these

regions can yield a more complete depiction of the true sacrifices and risks these communities face.

## 5.2 Introduction:

### *5.2.1 Hydropower Development*

In the cities where they are built, large dams are seen as a prospect for a brighter future and a symbol of prosperity (Ansar et al., 2014; Urban et al., 2015). Countries hosting large hydroelectric projects are oftentimes inspired by the promise of job creation and reduction in fossil fuel dependence. Aside from employment, other promised positive outcomes from construction include new hospitals and schools, improved water, health, and sanitation services, and overall regional economic development. However, there is great debate over the socioeconomic development of a country and the use of dams as a means to alleviate poverty. Often promoted with the idea that locals will gain numerous benefits (Moran et al., 2018), poverty has increased in the district where dams are built (Duflo and Pande, 2007; Pottinger and Hathaway, 2008). People displaced and disenfranchised by large hydropower projects can remain impoverished decades later. In Zambia, the Kariba Dam displaced approximately 57,000 whose livelihoods were impoverished for decades (Scudder, 2016, 2005). In other cases such as the Inga Project in the Congo Basin, and the Tucuruí and Belo Monte Dams in the Amazon Basin, the energy harvested largely bypasses consumers in the host cities and primarily benefits high use consumers such as mining and aluminum smelting companies and distant urban areas (Bosshard, 2015, 2013, Fearnside, 2006, 2001). Nonetheless, hydropower plays a leading role in the sustainable energy portfolios of developing countries (International Energy Agency, 2016).

In these countries, energy development makes part of the national agenda for economic development. At least 3,700 major dams with a capacity of more than 1 MW are either planned or under construction, primarily in countries with emerging economies (Zarfl et al., 2015). This proliferation of dams is most evident in the Amazon, Congo, and Mekong Basins, where proposed projects continue to emerge in order to harvest countries' substantial hydroelectric potential (Moran et al., 2018; Winemiller et al., 2016; Zarfl et al., 2015). These basins are perhaps the most biodiverse and important in the world. Second only to China, and as depicted in Table 5.1, Brazil remains the fastest growing country in new installed hydropower capacity in both 2016 and 2017 (International Hydropower Association, 2018a, 2017). Brazil has the largest installed hydropower capacity in South America (Table 5.2), comprising two thirds of the continent's total installed capacity. Hydropower in Brazil provides more than three-quarters of the nation's total electricity demand and the Brazilian Amazon Basin holds 42.2 percent of the country's total hydroelectric potential (Ministério de Minas e Energía and Empresa de Pesquisa Energética, 2015; Soito and Freitas, 2011). As part of government strategies to increase energy security, economic growth, and industrialization, Brazil has over 100 dams planned in the Amazon Basin (Luporini and Cruz, 2015; Timpe and Kaplan, 2017; Zarfl et al., 2015)

NEW INSTALLED CAPACITY BY COUNTRY*

| Rank | Country | Capacity added (MW) |
|---|---|---|
| 1 | China | 8,540 |
| 2 | Brazil | 3,866 |
| 3 | Pakistan | 2,487 |

* including pumped storage

**Table 5.1:** Where has hydropower capacity been added in 2017? *(International Hydropower Association, 2018)*

SOUTH AMERICA CAPACITY BY COUNTRY*

| Rank | Country | Total installed capacity (MW) |
|---|---|---|
| 1 | Brazil | 104,139 |
| 2 | Venezuela | 15,393 |
| 3 | Colombia | 11,837 |

**Table 5.2**: South America installed capacity. *(International Hydropower Association, 2018)*

### *5.2.2 Sanitation in cities hosting large hydropower developments*

While access to energy remains a concern and plays a key role in national development agendas, access to clean water and adequate sanitation services are of paramount importance in poverty alleviation, health, and well-being of nations. Sanitation remains an issue in many countries, with two billion people worldwide lacking access to these basic services (UNICEF and WHO, 2019). Areas with limited access to clean drinking water and sanitary infrastructure are vulnerable to diseases (Borchardt et al., 2003; Hunt et al., 2010; Verhougstraete et al., 2015; Weiss et al., 2016; World Commission on Dams, 2000), making this a pivotal issue in the protection of human health. Although capital cities often have higher coverage of basic services (UNICEF and WHO, 2019), a lack of water and sanitation infrastructure in smaller cities hosting large hydropower developments can be a reflection of the socioeconomic inequality observed in these places (Cushing et al., 2015). In Brazil, court mandated orders for sewage collection and treatment were addressed in 177 out of the 2,495 Brazilian municipalities lacking these systems. Litigation is concentrated in the richer cities (De Barcellos, 2014), denoting a lack of representation of the sanitation needs of poorer cities in the judicial system and further highlighting the social and economic inequality in services.

In the states of the Brazilian Amazon, socioeconomic inequality can be observed through the per capita income and human development index, which is lower than in the southern and southeastern states of Brazil (depicted in Figures 5.1 and 5.2) (Chediek et al., 2010; Instituto Brasileiro de Geografia e Estatística, 2011a; Instituto Brasileiro de Geografía e Estatistica, 2018; United Nations Development Programme Brasil, 2013). The provision of sanitation services in the states of the Brazilian Amazon lag behind the rest of the country with 55.4 percent of residents having potable water from a distribution network and only 10.5 percent receiving sewer services (Ministerio das Cidades, 2018). Under these conditions, and not unlike other dam hosting areas, residents in the region resort to water wells for their water supply and septic tanks for waste disposal (Gauthier and Moran, 2018). These septic tanks generally have an open bottom, allowing liquids to percolate through the soil and reach shallow groundwater resources. Large inflows of migrants arrive to host cities of large projects looking for the possibility of gaining construction or construction-related employment (Dos Santos Franco et al., 2018; Moran, 2016; World Commission on Dams, 2000). The increase in population brought by new hydropower development projects present a challenge to the already limited infrastructure in the Amazon region. Often given the most basic water and sanitation facilities, host communities suddenly face severe pressure on their services and infrastructures stemming from the sudden increase in population. Incoming residents build new wells and septic tanks to provide for their water and waste disposal needs, resulting in greater volumes of septic tank contaminants reaching the same groundwater resources that feeds drinking water wells.

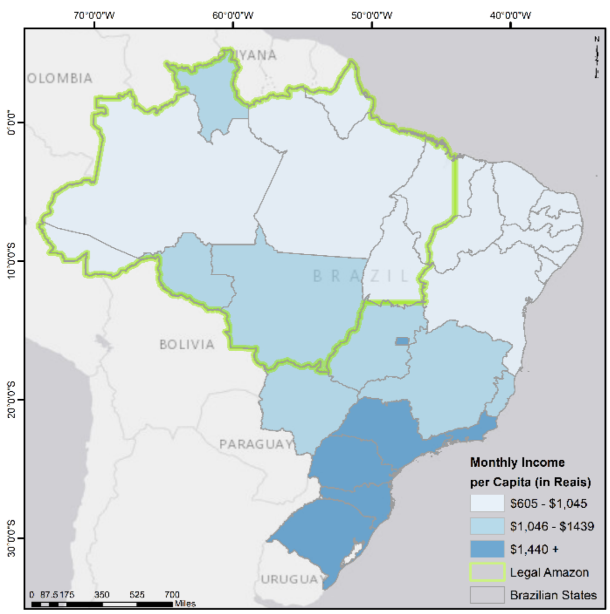


**Figure 5.1**: Monthly per Capita Income (in Reais) by State in 2018

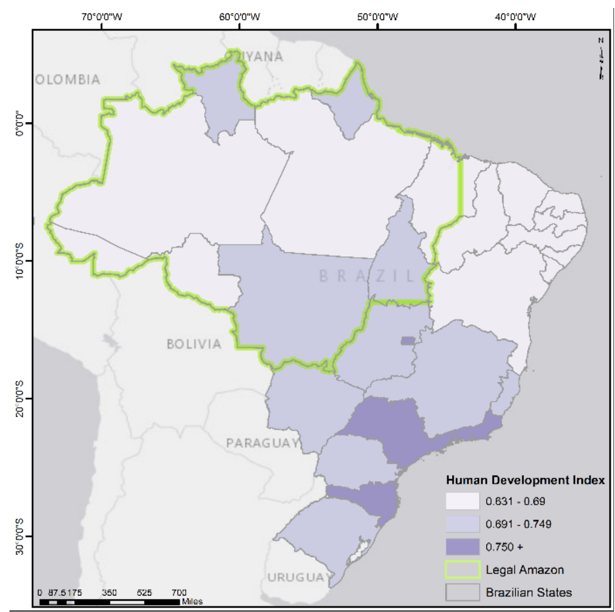


**Figure 5.2:** Human Development Index by State in 2010

Using biological and social data, this study analyzes the socioeconomic level of the population in a host city in relation to a household's exposure to, or ingestion of, fecal contaminants in drinking water wells in Altamira, host city of the Belo Monte dam. Bridging social and natural sciences, the connection between fecal contaminant exposure and ingestion across varying socioeconomic levels in Altamira is explored. The water and sanitation services witnessed in Altamira are similar throughout the Amazon region and in the developing world. In this sense, Belo Monte and Altamira serve as a model system for the analysis of relationships between social and environmental variables related to sanitation and quality of life in communities affected by major hydroelectric development projects. The need to minimize environmental and health issues arising from hydroelectric expansion becomes crucial as dams continue to play a significant role in sustainable energy portfolios of developing countries. The progression of basic sanitation in Altamira can yield insights to the role socioeconomic level in exposure and ingestion of contaminants throughout host cities and areas surrounding complexes such as Belo Monte.

### *5.2.3 Study Area*

The Belo Monte Hydroelectric Complex was born out Brazil's goal to secure a reliable power supply. It is the largest project in the Amazon region and third largest worldwide in terms of installed capacity. The hydropower project has the potential to generate an average of 11 gigawatts serving an estimated 60 million people across 17 Brazilian states. Located along the Xingú River in the State of Pará, the city of Altamira lies 52 kilometers upstream from Belo Monte and served as the main city hosting construction efforts (Figure 5.3). Belo Monte's construction began in 2011 with inauguration of the 14th turbine occurring in 2019 (Globo G1 Pará, 2019).

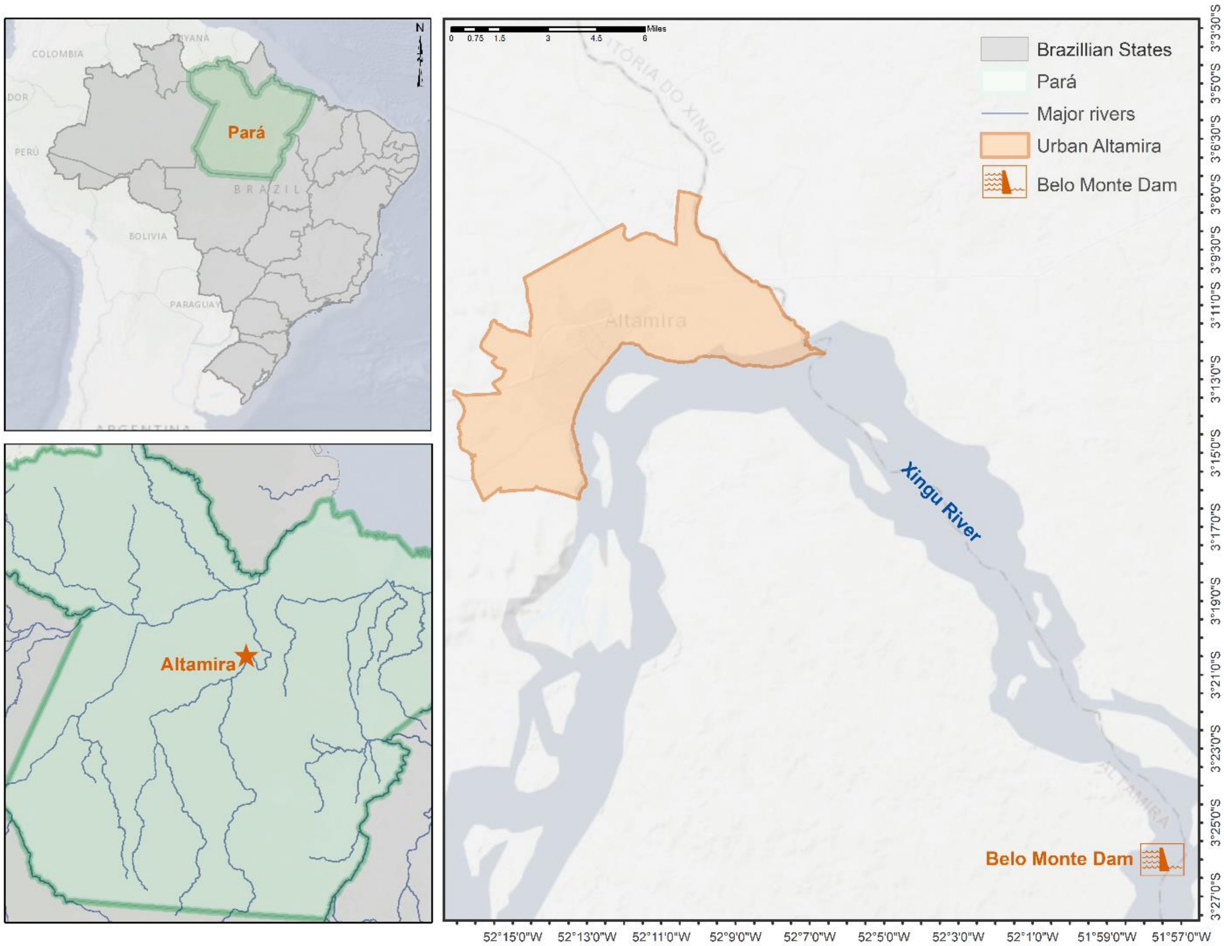


**Figure 5.3**: Study Region

The construction brought more than 30,000 workers to Altamira. Population rose from 77,439 inhabitants in 2010 to an estimated 109,938 in 2016 (Instituto Brasileiro de Geografia e Estatística, 2016, 2011a).

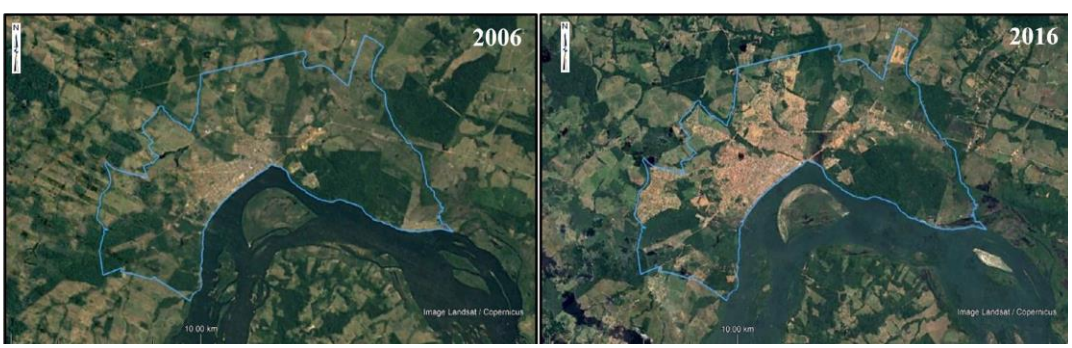


**Figure 5. 4**: Urban Growth in Altamira
*(Gauthier and Moran, 2018)*

The population increase brought forth by Belo Monte's construction (Figure 5.4) stressed the city's sanitation service, particularly through greater water demand, wastewater disposal, and solid waste generation (Gauthier et al., 2019). Although not everyone in the city has been connected to the water distribution network, Altamira's water treatment plant operates at well over half capacity (Gauthier and Moran, 2018). Further, the pump capacity of the city's lift stations was unable to serve higher altitude neighborhoods as the city continued to rapidly grow (Gauthier and Moran, 2018). The unreliability of the water distribution system is one very important driver for the dependency on household wells in Altamira. Irregular or no connection to the local water distribution system increases the dependency and density of water wells in the city (Gauthier et al., 2019; Gauthier and Moran, 2018). Households lacking connection to the local water distribution system, or receiving an irregular water service, resort to shallow-dug wells (Gauthier et al., 2019; Gauthier and Moran, 2018; Pará, 2016; Pessoa, 2016). The wells commonly dug in Altamira do not require a permit, are not registered, and while some are sealed, none are coated, putting them at risk for intrusion of contaminants. During the wet season, groundwater levels rise and in a previous study residents reported degradation in the quality of water with observable turbidity and a distinct smell, regardless of treatment (Gauthier and Moran, 2018). Building a coated well with layers of sand and rock has an average cost of $40 dollars per meter. Deeper wells, less susceptible to variations in the dry season, become a costly matter for most households in Altamira (Gauthier and Moran, 2018).

At the same time, similar to many Amazonian cities, open bottom septic tanks remain the preferred option for wastewater disposal (Gauthier and Moran, 2018; Pessoa, 2016). Altamira began as a small settlement that acted as a trading post during the rubber boom (1850-1920) and, by 1880, immigrants had settled between the streams now known as Ambé and Panelas. Since its establishment, the city never had a wastewater collection network and has discharged its sewage in open air ditches, septic tanks, or surface waters (Norte Energia S.A., 2011)**.** The majority of the population disposed of sewage in open bottom septic tanks that seep their effluents directly into the soil. These pits are close to the shallow wells and cisterns, which ends up compromising the quality of drinking water (Gauthier et al., 2019; Gauthier and Moran, 2018; Instituto Brasileiro de Geografia e Estatística, 2011b; Ministerio das Cidades, 2018; Norte Energia, 2011; Pessoa, 2016). Aside from five resettlement neighborhoods built for the families displaced by the dam, households in Altamira lacked connection to sewer services. Previous to their relocation, residents living near streams or surface waters disposed of their sewage directly into them without any treatment (Ministerio Publico Federal, 2017; Norte Energia, 2011; Pessoa, 2016; Procuradoria da República no Pará, 2016; Promotoria da Justiça do Ministério Público, 2018). Wastewater from the resettlement neighborhoods was collected in aboveground community tanks which were emptied into tank trucks and transported to the wastewater treatment plant, financed and operated by Norte Energia. The rest of the homes in the city had septic tanks constructed by their current residents, family members, past owners, or local independent handymen (Gauthier and Moran, 2018). Further, greywaters not coming from bathrooms are discharged directly to the surface or to neighboring water bodies (Gauthier and Moran, 2018; Ministerio Publico Federal, 2017; Pessoa, 2016). In the past, local commerce and business, including the hospital, discharged greywaters in that same manner (Pessoa, 2016). Direct discharges onto the river are not uncommon and of routine occurrence (Gauthier and Moran, 2018; Pessoa, 2016).

Residential water wells in Altamira feed off a single unconfined aquifer (CPRM Serviço Hidrogeológico do Brasil, 2014). The increases in population resulted in greater volume of septic discharges to the ground which can lead to contaminants leaching to the water below, ultimately reaching wells and putting the health of the population at risk (Gauthier et al., 2019; Ministerio Publico Federal, 2016; Pará, 2016; Risebro et al., 2012; Verhougstraete et al., 2015).

Using semi structured interviews with government officials, reports, and documents from government agencies, Altamira's evolving basic sanitation is summarized to observe its progress. Statistical analyses are performed to determine if connection to water and sewer services are dependent on socioeconomic level of a household. Further, results from fecal contamination markers found in residential wells throughout the city allow for the use of statistical analyses to determine the significance of socioeconomic level to a household's exposure to fecal contaminants in drinking water wells and to contaminant ingestion in the home.

## 5.3 Methodology:

Publicly available Federal and State Public Ministry records regarding legal proceedings of the basic sanitation systems in Altamira were reviewed to further understand the progress of water provision and wastewater disposal efforts within the city. Semi-structured interviews were performed with government officials at Altamira's Secretariat of the Environment (SEMAT), Sanitation Company (COSALT), Public Sanitation Department (DLP), and Secretary of Urban Planning (SEPLAN). Questions related to the current sanitation services provided by the city and hindrances in their provision were addressed.

In addition, 30 households in differing elevation and population density areas throughout the city were sampled and surveyed. Homes were chosen using Elevation as a proxy for shallowness of the aquifer in the area, and Population Density as proxy for clustering of water wells and septic tanks, which shortens transport time between septic contaminants and neighboring wells. Water was sampled from the households' drinking water wells in both the dry and rainy seasons. Samples for the dry season were taken in late September and early October 2018 while samples from the rainy season were taken in late February 2019 and early March 2019. Analyses for specific fecal markers, *E. coli* and *B. theta*, were performed for each sample to determine presence and magnitude of fecal contamination in each household water well (Gauthier, 2020).

The survey applied in the households served to collect data on water use and treatment, waste disposal practices of residents, sanitation services provided, and socioeconomic level of the home. Drawing from the Brazilian Economic Classification Criterion (Associação Brasileira de Empresas de Pesquisa, 2016), and incorporating regional idiosyncrasies, indicator variables were evaluated to establish Altamira's socioeconomic strata and place households in a socioeconomic scale. Information was collected on particular income indicators with variables including, but not limited to: federal aid received, domestic workers employed, and automobile and motorcycle ownership. A monetary value was attributed to a household's transportation assets using Brazil's Economic Research Institute database (Fundação Instituto de Pesquisas Econômicas, 2018). Information on demographic conditions also served as socioeconomic indicators, mainly, the ratio of salaried household members to the total number of people in the household. All socioeconomic and sociodemographic data is based on self-reports although direct visual observations were made during household visits.

Aside from self-reported data, the socioeconomic level of a household was supported through observations of construction materials of the roof, finished flooring, plastered walls, painted walls, and in-room bathrooms in the home. After each visit, households were placed on a scale from 1 to 9 based on observations and upon consensus of all field research assistants. Once all 30 households were interviewed, the full socioeconomic range of the sample was observed. Taking into account numerical values such as transportation assets and salary ratios, in addition to the initial visual observations, and the full range of socioeconomic classes within the sample, all household rankings were reviewed and reappointed within the scale if necessary. Visual observations were rated, and ultimately grouped into classes. Household class profiles are shown in Table A.7 of the Appendix.

Statistical analyses for results were performed using R and STATA software, while all maps were completed in ArcGIS Desktop. Progression and changes in water distribution and disposal networks made between 2016 and 2018 are explored through the examination of aforementioned official documents. Mann Whitney, Spearmank Rank and Pearson Chi Squared tests are applied to determine relationships between multiple variables within the sample, while Generalized Linear Regression models are perfromed to determine associations between socioeconomic scale and connection to services, contaminant presence, contaminant concentration, water treatment, purchase of water, and other variables related to exposure and ingestion of contaminants.

## 5.4 Results and Discussion

### *5.4.1 Changes in Water Distribution and Disposal Networks*

#### ***5.4.1.1*** *Water Distribution*

The Belo Monte dam was granted a Construction License under the condition that the water and sanitation systems in urban Altamira would be improved by June 2014, two years after dam construction began. This requirement had not been met when an Operation License (no. 1317/2015) was granted on November 24, 2015 (Gauthier and Moran, 2018). The Operation License dictated that all households in urban Altamira were to be formally connected to the potable water network and sewer system by September 30, 2016. Yet as of 2019, this work had not been completed. Areas not receiving water services have wells or are supplied water by tank trucks, which do not provide a fixed water distribution schedule. In some instances, the tank truck driver unofficially charges residents for the distribution of water (Gauthier and Moran, 2018). This puts socioeconomically disadvantaged households in a precarious situation regarding their access to water. If a household does not have the capital to invest in a well, it relies on tank truck services. Particularly vulnerable, are unserved residents in high elevation neighborhoods, which require deeper wells. The cost of digging a well is done by the meter, meaning that residents in higher elevation areas incur greater costs digging deeper wells.

Belo Monte's construction consortium, Norte Energia, made improvements and is working on expanding the city's water distribution network and treatment plant capacity (Promotoria da Justiça do Ministério Público, 2018). The water treatment plant was initially established in 1984 and Norte Energía has invested in increasing water intake volume, cleaning and structurally reinforcing tanks and filters in the water treatment plant, structurally reinforcing and replacing piping system for the water receiving tank, building a 15,000-liter reservoir tank, enhancing water boosters, and drilling a new artesian well. Norte Energía has also improved 8 water reservoir tanks and 6 lift stations providing 7 booster pumps, and has expanded the water distribution network (Promotoria da Justiça do Ministério Público, 2018). Nonetheless, operational limitations remain, reducing the amount of water that can be treated and distributed per day.

Interviews with COSALT personnel, and publicly available documents, reveal that failures in the equipment and theft of booster pumps in lift stations are problematic and recurrent issues in the adequate and reliable provision of water distribution. Further, current water treatment plant capacity has not been able to keep up with the rapid growth in population. A letter from Norte Energia to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) dated August 26, 2018 (no. 02002.015825/2016-10) indicates that past improvements made to the water network were based on a projected water usage of 168 liters per person per day. This was above Brazil's national water consumption average of 149.7 liters per person per day, as indicated by the Brazilian Institute of Geography and Statistics (IBGE) and the National Sanitation Information System (SNIS) (Promotoria da Justiça do Ministério Público, 2018).

However, water demand in Altamira is greater than expected reaching up to 811 liters per person per day in certain neighborhoods. This is not surprising. The use of water in most Amazonian communities is greater than in other Brazilian regions. Rooted in a water abundant environment, residents tend to have their own wells and don't monitor nor pay for water consumption. The heat and humidity in the region play a role in higher water use. Multiple showers a day are common, and residents regularly clean dust from unpaved streets in their homes with abundant water. Perhaps not yielding to these cultural idiosyncrasies and social considerations, Norte Energia reports that water use for cities between 50,000 and 500,000 residents, such as Altamira, is 150 liters per person per day. COSALT strongly differs, stating that according to their calculations, Altamira residents consume approximately 268 liters per person per day (Promotoria da Justiça do Ministério Público, 2018). Regardless of the exact number, Altamira's potable water use is above average.

Norte Energia carried out viability studies to increase the output volume of Altamira's water treatment with the installation of two compact water treatment systems and an expansion to the current physical plant. The current water treatment plant has a capacity of 180 liters per second. Suggesting 130 liters per person per day as the design volume for their expansion, Norte Energia plans to increase output by providing two compact treatment plants, each averaging 90 liters per second of treated water. The initial timeline for this joint effort with the municipality was to purchase equipment by December 2017 with full operation of both compact systems planned for May 2018. In October 2018, a sixty-day extension was granted to Norte Energia, yet as of June

2019 both compact systems were not fully installed and operational. The expansion to the physical plant is set to begin in 2021 and will increase 90 liters per second of treated water to the current 180 liters per second. These plans will potentially expand the capacity of the current water network from 180 liters per second to an average of 450 liters per second of water treated, increasing the ability to serve more households. IBGE's estimated population in Altamira is 110,000 residents as of 2016. With this number, and assuming the water treatment plant operates for 16 hours each day, the increase in water treatment would allow each resident to consume 235 liters per day. However, if Altamira's population were to increase to 150,000 residents, water consumption per resident would be constricted to 172 liters per day.

#### ***5.4.1.2*** *Water Disposal*

Altamira is not included in the State of Pará Sanitation service area, making the public sewage system almost nonexistent (Norte Energia, 2011). Belo Monte's arrival promised a sewer system for Altamira as one of the conditions of the project's Operation License. Norte Energia was to provide a sewage network for the city while also emptying and decommissioning all septic tanks in the urban area. Resettlement neighborhoods were the first to have a sewage collection network established, where all wastewater was collected and stored in tanks for transportation to the wastewater treatment plant via tank trucks. Norte Energia built a wastewater treatment plant and a sewage network for the city, yet homes were not connected to the system. Norte Energia claimed that intra-domiciliary connections were the responsibility of individuals or, at best, of the municipality. Litigation between the Municipality of Altamira and Norte Energia delayed connections but Norte Energia ultimately began connecting urban households to the sewage network at a slow pace in September 2017 (Promotoria da Justiça do Ministério Público, 2018). These connections did not encompass the totality of Altamira's residents and did not include collection of greywaters. Interviews with personnel from Altamira's Secretariat of Urban Planning (SEPLAN) revealed that Norte Energia consistently reported the connections being made, yet only addresses were included with no coordinates or maps shared for locational reference. This poses a problem because Altamira's explosive growth yielded repeated street names and altered neighborhood boundaries. These changes make it difficult to pinpoint homes connected to the system based on address alone.

Norte Energia disseminated awareness campaigns via radio and TV, making clear to residents the importance of connecting to water and sewage networks. Regardless, some residents refused to connect to the system due to potential charges for water and sewer services and in fear of having their current systems, reliable ones they had known and used their whole lives, decommissioned. Other residents, while willing, were unable to connect because piping to the sewer main required access to neighboring properties, who refused sewage pipes be laid through their property. Aside from gaining permission, Norte Energia performed additional rounds of visits to homes in Altamira in order to collect measurements and assess materials required for each household to be connected. Publicly available documents from the Federal Justice Court revealed that turnover for the companies contracted to connect households to the sewage network was high, mainly due to difficulties in following imposed schedules. As of January 2018, three companies were working in different parts of the city, yet as of May 2019, connections were still unfinished.

Norte Energia's investment in Altamira's sewage system included a wastewater collection network, 13 pump stations, a wastewater treatment plant, a treated effluent pump station, and an outfall. The plant built and operated by Norte Energia is a secondary wastewater treatment plant, with removal of settleable solids and biological removal of dissolved and suspended organic compounds. A visit to the wastewater treatment plant was not possible, but an audit conducted in

February 2017 by Altamira's Secretariat of the Environment (SEMAT) was available through public records. Notes and photographs illustrated what seemed to be a precariously improvised laboratory, with a microwave and plastic table in the corner of the room. Far from a sanitary environment, this concerned SEMAT and SEPLAN personnel. The audit exposed concerns regarding the laboratory and, therefore, the quality and reliability of water testing results.

As expected with any project, the first sewage system in Altamira's history began operating in a series of trial and error attempts. Reports of broken pipes and valves, or backflow to homes were common during the first months of operation. Although there are many reasons that account for these problems, the high contractor turnover and lack of continuity, as well as the amount of time the collection network remained unused while litigation took place, were contributing factors. The wastewater treatment plant now serves homes outside of the resettlement neighborhoods yet records reviewed do not indicate any expansions. Norte Energia designed the plant with a contribution of approximately 160 liters of wastewater per person per day (Promotoria da Justiça do Ministério Público, 2018) as stipulated by the Brazilian Technical Standards Association Rule NBR 7229/1993 (Associação Brasileira de Normas Técnicas, 1993). However, on occasion, the effluent quality has exceeded the parameters established to discharge and fines have been issued for polluting the Ambé stream and Xingu River. Norte Energia's response indicated that these were isolated incidents caused by 2 malfunctioning pumps and a strangled pipe, which were repaired. Previously, Norte Energia received a fine of 2,500,000 reais (approximately $773,000 USD) for direct sewage discharges from the Jatobá resettlement neighborhood. IBAMA had also imposed a fine of 7,500,000 reais ($2,325,986 USD) to Norte Energia for failing to provide household connections to a sewage system in urban Altamira (Assessoria de Comunicação do IBAMA, 2017; Gauthier and Moran, 2018).

### *5.4.2 Socioeconomic Level and Connection to Services*

The inequalities on the distribution of income, wealth, and other economic variables in Brazil and the Municipality of Altamira are evident in their GINI index of 0.53 and 0.56 respectively (United Nations Development Programme Brasil et al., 2010; World Bank, 2017). The GINI index is the most widely cited measure of inequality (United Nations Development Strategy and Policy Analysis Unit, 2015). Ranging from 0 to 1, it measures the extent to which economic disparity deviates from complete equality. While slightly less unequal in their distribution of wealth than the country as a whole, Altamira's human development index of 0.665 remains below the national average of 0.727. The state of Pará itself, and others in the Amazon region, show development indices lower than the national average (United Nations Development Programme Brasil et al., 2010). Taking these local realities into consideration, a socioeconomic measure for the homes sampled within the city of Altamira was performed using a combination of demographic and income indicator variables and observations. The distribution of the socioeconomic level and rankings of the households sampled is shown in Figure 5.5. The scale was divided to reflect approximate class categories within the sample.

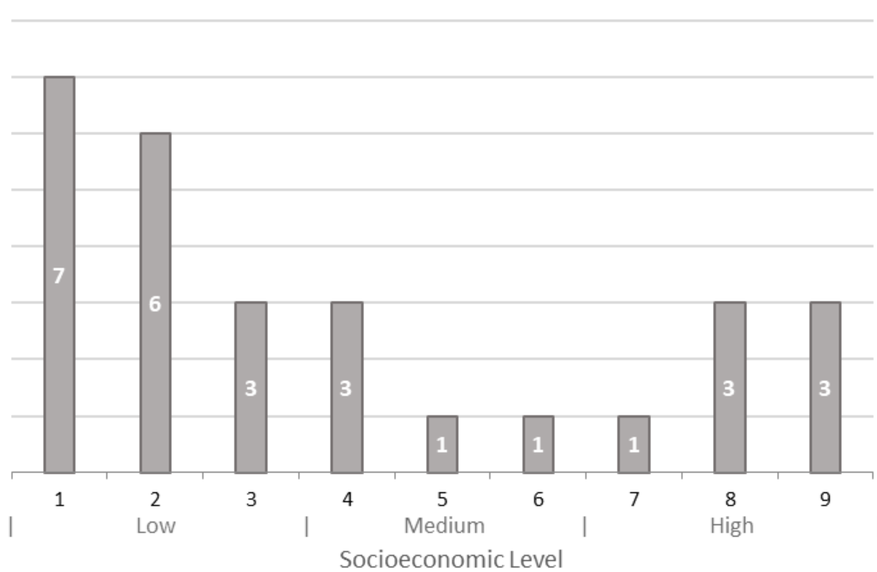


**Figure 5.5**: Distribution of homes by socioeconomic level

As depicted in Figure 5.5, the social distribution does not follow a typical bell pattern with a larger middle class. This is due to the bias within the sample. In order to perform water sampling, it was a requirement for participating homes to have unsealed wells and be located within the urban boundaries of Altamira. Additionally, to authorize placement of measuring equipment in the well, residents had to be owners of the property. This clearly biases the socioeconomic levels of the population sampled, where the extremely impoverished residents are not captured. Similarly, Altamira's most lucrative enterprise is rooted in the production of cocoa and cattle with wealthy landowners located far from the urban boundaries of the city. Therefore, the economic distribution observed in the sample captures differences within the middle class yet excludes socioeconomic extremes.

Descriptive statistics of the sampled homes are provided in Table A.8 in the Appendix. Value of Transportation and Salaried Ratio were grouped into 3 categories based on their distribution. Distribution, mean, and standard deviation for these variables are also detailed in the Appendix Figures A.4 and A.5. As expected, a Spearman correlation test shows a strong relationship between the Number of Residents and the Number of Families living in the household (p value = 7.591e-05, rho = 0.659). Further, the Salaried Ratio variable is derived from Number of Residents in the home over Number of Working Members; therefore, all three variables are correlated. Taking into account the multicolinearity that exists between the aforementioned variables, multivariate regressions were avoided and bivariate regressions were performed. Treating socioeconomic scale as a numerical variable, generalized linear model regressions were performed on each of the 14 predictor variables. Ultimately, the most significant predictor variables of socioeconomic level in homes are number of bathrooms in the home, plastered walls, painted home, roofing material, domestic help, and value of transportation. Regression results are detailed in the Appendix Table A.9.

Public records and resident accounts show that potable water connections in Altamira have increased, yet only 9 out of the 30 interviewed households reported being connected to the city's water network. This is due to the bias in the sample towards homes owning a well for water sampling. In the sampled homes, 26 wells had been dug by "well diggers" and 4 were built by home owners, neighbors, or family members. Nonetheless, COSALT continues to face problems with the reliability of their services as shown in the sample, where only 1 out of the 9 households connected to the city's network reported continuous water services. Mann Whitney, and bivariate regression results showed no statistical significance between connection to water services and socioeconomic level rankings. Although connected, some residents choose not to use the distribution network due to a perceived unreliability of services and inferior water quality, as revealed in interviews. Thus, socioeconomic level does not necessarily influence if a home is relying on these services.

Irregularity of water services is observed in households from all socioeconomic levels but differences in access to water remain. In more privileged homes, income is not a hindrance in increasing the depth of, or providing maintenance to, existing wells or even replacing pumps quickly, if needed. Further, multiple storage tanks or tanks with greater capacity can be readily purchased and installed in households of greater socioeconomic ranking, increasing their water storage. Therefore, on occasion where there is irregularity in water supply, their wells can suffice and these homes are not as strongly affected as perhaps other lower socioeconomic level households.

While the water distribution network has been established a longer period of time in Altamira, the sewage network is relatively new. Nonetheless, 16 out of 30 households in the sample were connected to the sewage network. Nine of the homes connected to the sewage system had done so within the last year (2018). One home had been offered a connection which had not yet been completed. In the homes where connections were made, Norte Energia decommissioned existing septic tanks. This process had not been done in the homes that were removed from the reservoir flood zone. Perhaps influenced by this past occurrence, review of public documents revealed that Norte Energia proposed completing sewage connections first in areas deemed as sensitive due to their flooding history (Promotoria da Justiça do Ministério Público, 2018).

Both Mann Whitney (p-value = 0.02178) and bivariate regression results (Table A.9) confirmed a statistical significance between socioeconomic ranking and connection to sewer services. Of the homes not connected to sewage services, 11 were in the low socioeconomic category. A Pearson Chi Squared Test revealed a statistically significant relationship between low socioeconomic level homes and sewage connections (X-squared = 4.9512, df = 1, p-value = 0.02607), suggesting that higher income homes are more likely to have sewage services (see Figures 5.6 and 5.7). Given the small size of the sample, it is worth mentioning that more extensive sampling is required to confirm the generalizability of these relationships.

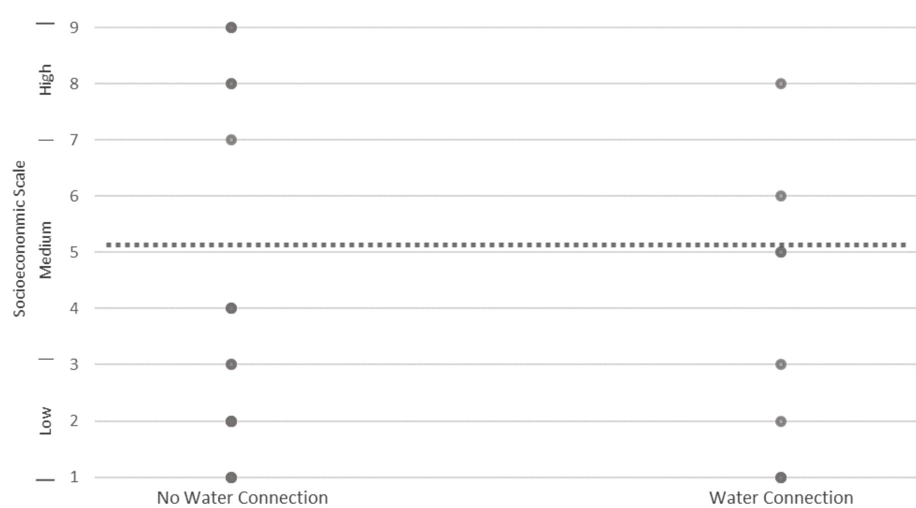


**Figure 5.6:** Connection to potable water services by socioeconomic level

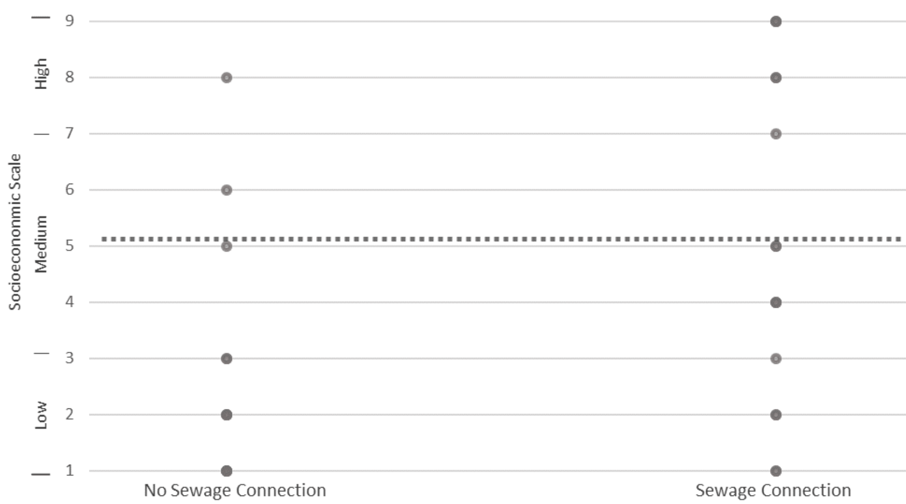


**Figure 5.7:** Connection to sewage services by socioeconomic level.

### *5.4.3 Socioeconomic Level and Contaminant Exposure*

Being a small city in the Amazon region, Altamira neighborhoods do not conform to a strikingly divisive social structure nor is zoning based on socioeconomic level or income. A mix of high, medium, and low socioeconomic households coexist within the same block (See Figure 5.8). Results indicate that the socioeconomic ranking of a home is not dependent on the population density of the area where the household is located. Therefore, contaminants from septic tanks can reach neighboring water wells irrespective of the socioeconomic level of a home. Until recently, all socioeconomic levels shared sanitary similarities. Due to the irregularity of potable water services, most homes were dependent on water wells for their drinking water and a lack of a sewage network meant every household had a septic tank to dispose of their sewage. In the homes sampled, 11 septic tanks had been built by handymen, 11 were built by home owners, neighbors, or family members, and only 1 was built by a no longer existing Office of the Superintendent of Public Health Campaigns (SUCAM). Seven homes reported not knowing who built their septic tank as it was there prior to their tenancy.


**Figure 5.8**: Varying socioeconomic levels in Altamira

Regardless of the socioeconomic ranking of a home, the neighboring distance of water wells to septic tanks can facilitate contaminant transport. Regression results (Table 5.3) presented a statistical significance between socioeconomic ranking and presence of *B.theta* during the dry season in the homes sampled. While the small size of the sample restricts the capacity to make statistical comparisons, the data presents inclinations regarding the exposure to contaminants in sampled households. Table 5.4 shows the percentages of homes in each category testing positive for fecal contaminants by season. An increase in the presence of *E.coli* is observed in the sample during the wet season, regardless of socioeconomic level. The spatial reach of *E.coli* increases during this season as rains facilitate contaminant transport (Gauthier, 2020). Nonetheless, rains also reduce the concentration of *E.coli* through dilution.

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| ***E.coli* Concentrations** | | |
| Dry Season | 0.060 | (-0.598 - -0.002) |
| Wet Season | 0.854 | (-0.062 - 0.0513) |
| ***B.theta* Concentrations** | | |
| Dry Season | 0.039* | (-0.129 - -0.007) |
| Wet Season | 0.756 | (0.054 - 0.075) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table 5.3**: Generalized Linear Model Regression Results for Socioeconomic Levels on Presence of *E.coli* and *B.theta* in the dry and wet seasons

| | *E.coli* Presence | | *B.theta* Presence | |
|---|---|---|---|---|
| Soc. Level | Dry Season | Wet Season | Dry Season | Wet Season |
| Low | 69% | 75% | 63% | 25% |
| Mid | 86% | 100% | 29% | 71% |
| High | 29% | 57% | 14% | 29% |

**Table 5.4**: Homes exposed to contamination (presence of *E.coli* and *B.theta*)

Figures 5.9 reveals that for the homes positive for *E. coli* in the dry season, concentrations seem to decrease as social class increases and higher socioeconomic level households show lower concentrations of *E.coli*. However, these differences in contaminant concentrations between socioeconomic classes are not evident in the wet season (Figure 5.10). A Spearman Rank correlation test indicated a statistically significant negative moderate relationship between socioeconomic level ranking and *E.coli* concentrations in the dry season (S = 6769.8, p-value = 0.004326, rho = -0.5060837). A statistically significant negative moderate relationship was also found between socioeconomic level ranking and *B.theta* concentrations in the wet season (S = 6366.4, p-value = 0.02211, rho = -0.4163285). Figures 5.11 illustrates that in the dry season, greater concentrations of *B.theta* are observed as socioeconomic ranking decreases. *B.theta* concentrations appear lower in higher socioeconomic level households both in the dry and wet season (Figure 5.12) , revealing a decrease in *B.theta* concentrations as socioeconomic class increased.

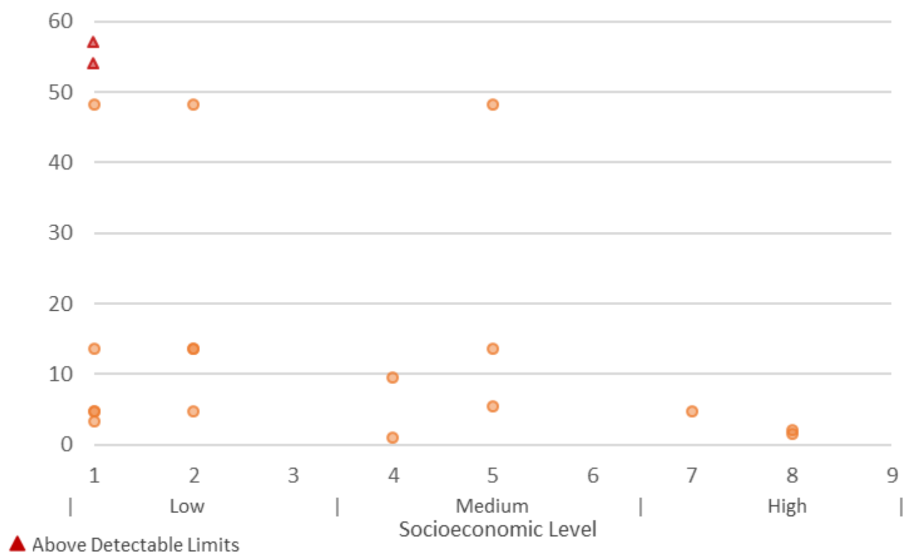


**Figure 5.9**: *E.coli* concentrations in the dry season by socioeconomic level.

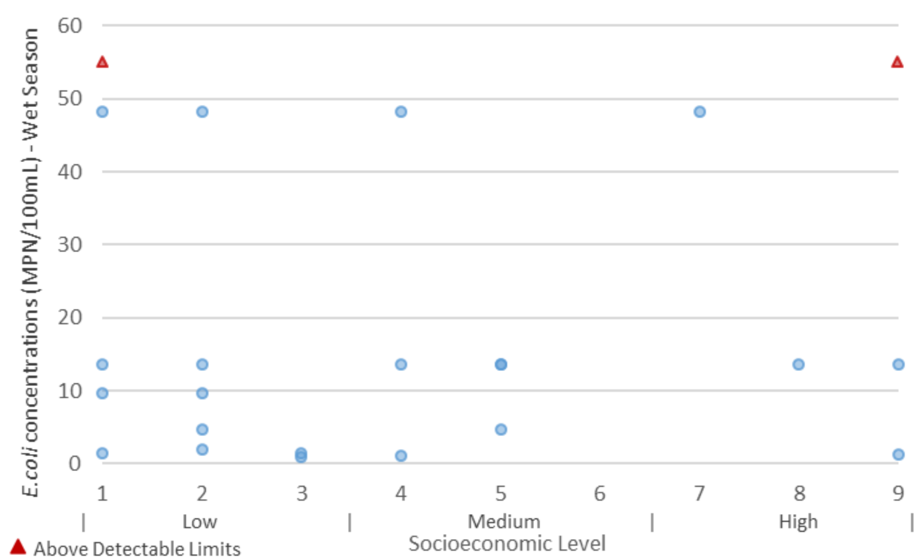


**Figure 5.10**: *E.coli* concentrations in the wet season by socioeconomic level.

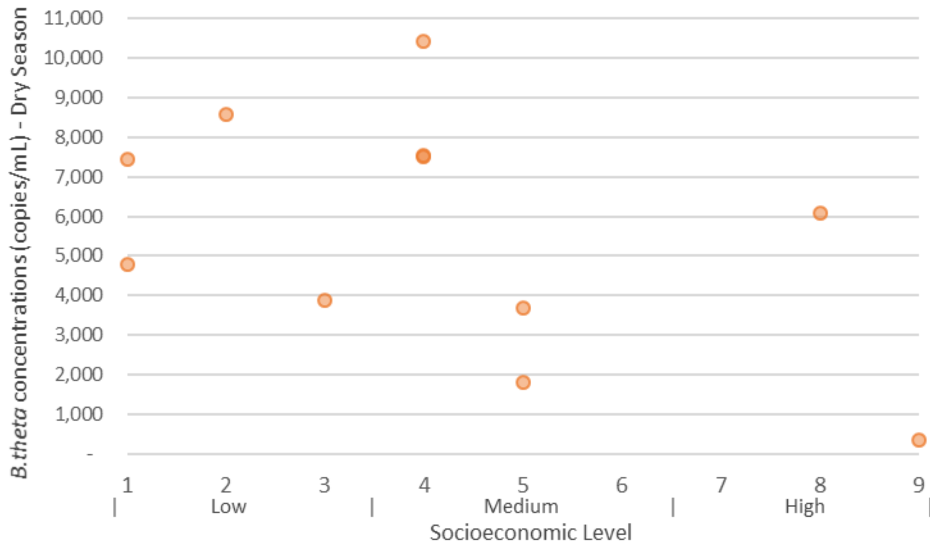


**Figure 5.11**: *B.theta* concentrations in the dry season by socioeconomic level.

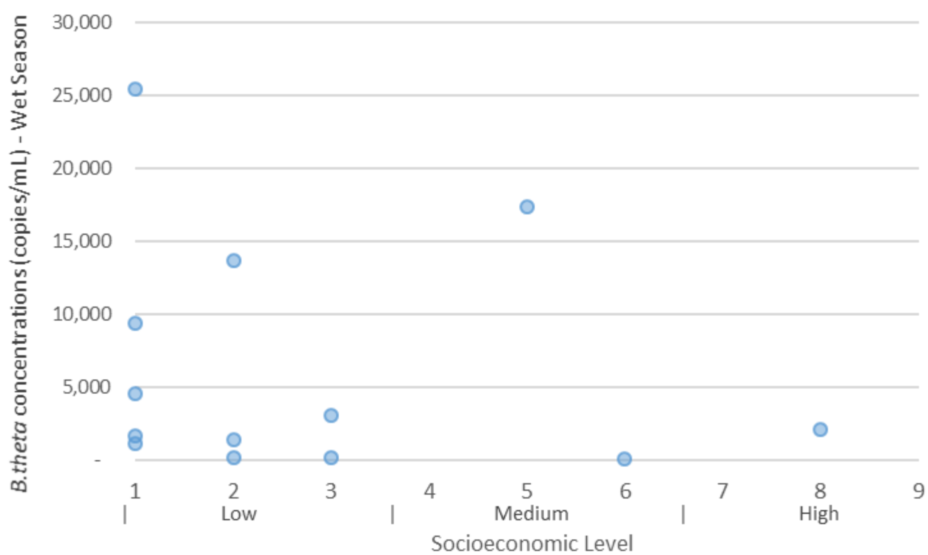


**Figure 5.12**: *B.theta* concentrations in the wet season by socioeconomic level.

### *5.4.4 Socioeconomic Level and Contaminant Ingestion*

Given that there is no spatial stratification of socioeconomic class in the study area, a household's exposure to fecal contaminants from neighboring septic tanks is not dependent on socioeconomic level. The differences in the ingestion of fecal contaminants within the households is likely to come from the ability of households to treat their water and protect themselves from ingesting contaminants. Homes of differing socioeconomic level have different resources available for not ingesting potentially contaminated well water. Reducing the risk of pathogen ingestion can be attained through: 1) connecting to COSALT's distribution network, 2) purchasing bottled water, or 3) resorting to water treatments such as boiling, chlorination, or filtration. Two main assumptions are that the bottled water purchased by the homes is produced according to best practices and is free of bacteria and that COSALT's services continuously maintain water quality standards. Further, in-home treatments such as boiling, chlorination, and filtration are assumed to be carried out adequately and equipment (i.e. filters) changed and maintained properly.

Boiling, chlorination, and filtration where the treatment options observed in the 14 homes that reported treating their drinking water. Mann Whitney, and regression results (Table 5.5) indicated no statistically significant relationship between socioeconomic scale and water treatment. Additionally, 6 homes reported purchasing bottled water, and 10 homes neither purchased or treated their drinking water. The 6 homes that reported purchasing water were from varying socioeconomic categories, but none of the homes pertained to levels 1 and 2 of the scale. Mann Whitney results revealed a statistical significance between water purchase and socioeconomic scale (both p-values = 0.02935). Higher socioeconomic level homes treated or purchased their drinking water, minimizing the risk of contaminant ingestion (see Figure 5.13).

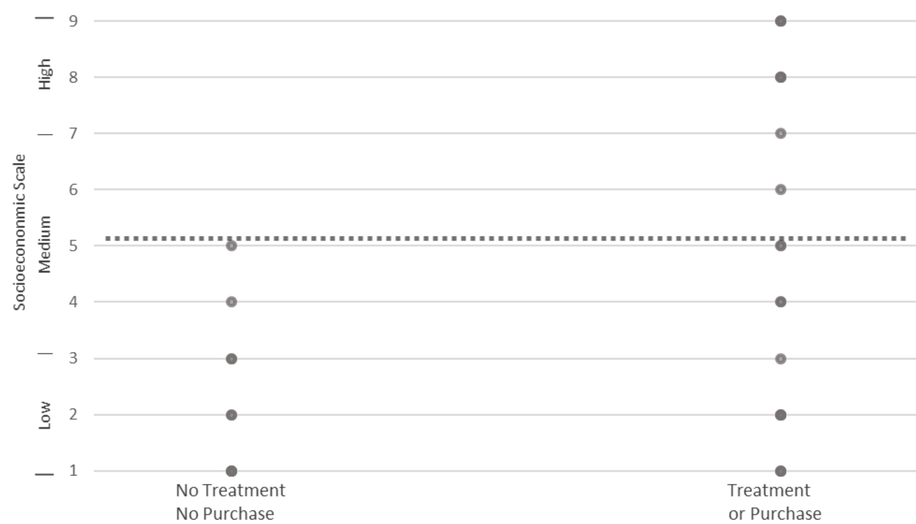


**Figure 5.13**: Social scale and treatment or purchase of drinking water as ways to reduce ingestion of contaminants.

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| **Connection to Water Services (ref = No)** | | |
| Yes | 0.923 | (-0.065 - 0.058) |
| ***Water Treated*** **(ref = No)** | | |
| Yes | 0.170 | (0.071 - 0.522) |
| ***Water Purchased*** **(ref = No)** | | |
| Yes | 0.045* | (0.030 - 0.758) |
| ***Water Treated or Purchased*** **(ref = No)** | | |
| Yes | 0.048* | (0.063 - 0.910) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table 5.5**: Generalized Linear Model Regressions for or Social Scale on Water Treatment, Purchase, and Connection to Services

The most accessible method of treatment observed in our sample was boiling, which has proven effective in destroying waterborne pathogens. The World Health Organization Guidelines for Drinking Water Quality recommend bringing water to a rolling boil to assure high temperatures are reached and achieve pathogen destruction (World Health Organization, 2015). Nevertheless, only 3 homes within the sample reported using boiling as their main water treatment option. Boiling requires consumption of energy so the availability, cost, and sustainability of fuel play a role in a household's choice of boiling water as a treatment option. In areas of the world where biomass or fossil fuels are in limited supply and must be purchased, the cost of boiling water turns prohibitive. However, in places such as Altamira, where affordable sources of fuel are available, boiling becomes an effective and accessible method of treatment. According to interviews, residents found it time consuming or did not like the taste of boiled water.

Chlorination of water was reported in 4 of the homes surveyed. Depending on its concentration, adding just 2 drops of chlorine per liter of water deactivates most pathogens – making it an economically accessible and simple treatment option (Environmental Protection Agency, 2017). When used to disinfect drinking water, chlorine has shown reduction of household diarrheal diseases in developing countries (Sobsey, 2002). Suspended matter diminishes the efficacy of chlorine as a water disinfectant. Hence, gravity settling of highly turbid water is recommended as a pre-treatment for households disinfecting with chlorine. The evaluation of adequate chlorination practices in the homes sampled was beyond the scope of this study. However, in 2 of the homes interviewed, residents disclosed dumping chlorine directly into the well without knowing the turbidity or volume of water for correct dosage. Nonetheless, for the purpose of data analyses, this study considers chlorination as an acceptable form of water treatment in the reduction of pathogen ingestion.

Filtering was the primary treatment option in the homes sampled, with 10 homes filtering their drinking water across all socioeconomic levels (Figure 5.14). The most common was the ceramic filter, mainly made of clay. These filters can result in substantial improvements in the microbial quality of drinking water, even in the absence of improved sanitation (Bulta and Micheal, 2019; Mwabi et al., 2012). Ceramic filters require cleaning on a regular basis to prevent clogging and biofilm growth (Sobsey, 2002). In order to work properly, the filters cannot have any cracks or structural damage as not to affect their efficacy in removal of contaminants. Pathogen removal efficiency varies depending on the pore size of the material. While the evaluation of filter conditions in the homes sampled was not within the scope of this study, filtration is considered an acceptable form of water treatment in the reduction of pathogen ingestion for the purposes of analyses.

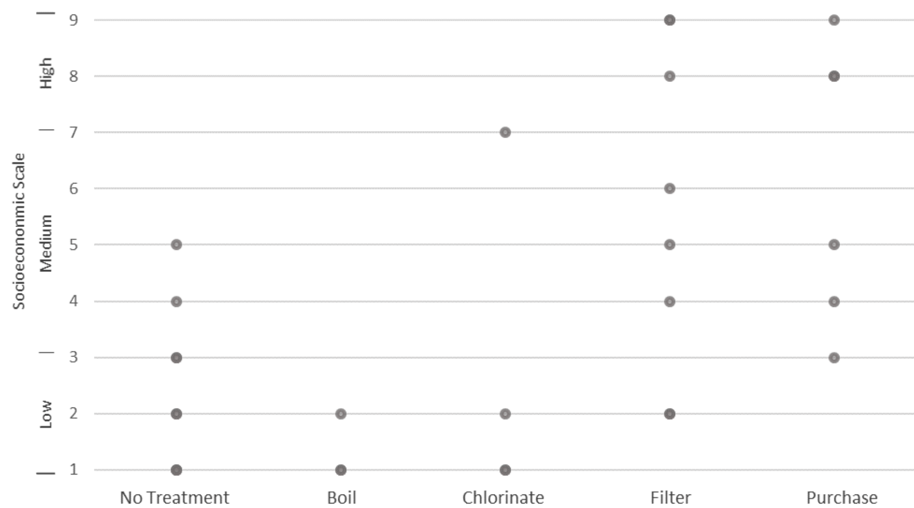


**Figure 5.14**: Socioeconomic Rankings and Water Treatment or Purchase

Avoidance of contaminant ingestion through filtering and water purchase is observed in varying socioeconomic levels but not in homes ranked lowest. Data suggests that higher ranked homes use filtering as their preferred water treatment and some purchase water to avoid contaminant ingestion. Although homes not treating their water are observed more frequently in lower ranked households, those that do treat their water by boiling and chlorination still avoid ingestion of contaminants. Bivariate regression between socioeconomic level and potential ingestion of contaminants indicated no statistical significance between the aforementioned variables (Table A.10 of the Appendix).

## 5.5 Conclusion

While there was no statistical significance between socioeconomic level and connection to water services, the irregularity of such services affect lower socioeconomic homes more than others. Socioeconomic differences in the access to water are observed, first and foremost by the economic capital needed to dig a well to supplement COSALT's irregular services or dig an existing well deeper to ensure water during dry months. Pump maintenance, acquisition of storage tanks, or bribes to tank truck drivers are also factors affecting water access in irregularly served areas of the city. Lower socioeconomic level households located in high elevation areas are particularly vulnerable to limitations in water access, as they may require deeper wells which are priced by the meter.

Norte Energia's initial underestimation of water use in the region, along with other design and operational shortcomings, led to scarcity of services and has required an increase in the capacity of the water treatment plant. The execution of these expansions in the system's volume have been slow and riddled with extensions. Similar hindrances were observed in sewage services. While the water distribution network has been established longer and displays no link to socioeconomic level, connections to the sewage network indicated the opposite. Perhaps due to its recent development, connection to sewer services were observed less in the lower socioeconomic ranked homes. This is particularly important for the water quality of the region. Continuous litigation and hindrances in the connection of homes to sewer services only aggravates groundwater quality in the city. Regardless of socioeconomic level, households coexist within the same block and contaminants from septic tanks can reach neighboring water wells irrespective of the socioeconomic ranking of the home. Socioeconomic level is not dependent on the population density of the area where the home is located. Nonetheless, significance was found between socioeconomic level and presence of *B. theta* in the dry season. No other season or contaminant showed relationships to socioeconomic scale. Further, lower *B.theta* concentrations were observed in higher socioeconomic level homes during both seasons, indicating *B.theta* was present in higher socioeconomic households at lesser concentrations.

A household's exposure to contaminants in their drinking water wells is not directly related to a socioeconomic level, but a relationship was observed between socioeconomic level and treatment of water in homes. This suggests that homes of higher socioeconomic ranking, which were observed to purchase or filter their drinking water more than their counterparts, are less at risk of contaminant ingestion. Boiling, chlorination, and filtration were the main water treatment options observed, but purchasing water was also considered an appropriate way to avoid contaminant ingestion. Water purchases not limited to a particular socioeconomic scale, but boiling and chlorination were observed mainly in lower socioeconomically ranked households. Water treatment is observed more frequently in higher socioeconomically ranked homes but lower ranked households can still avoid ingestion of contaminants by adopting boiling and chlorination, both accessible water treatment options. Nonetheless, the willingness of homes to pay for any water treatment technology is dependent on their financial affordability and ease of use, both important factors on the willingness of a home to treat their water. The introduction of water treatment technology without consideration of the socio-cultural aspects of the community and without behavioral, motivational, educational and participatory activities is unlikely to be sustainable. Therefore, initiatives in water, hygiene and sanitation must include community participation, education, and behavior modification.

Improvements to the water and sewage networks are underway, yet there is still much to be done in order to provide equal and just sanitation services to the totality of the population. From litigation and past postponement of sewage services, it is clear that homes not connected under Norte Energia's current efforts, will remain without these services for an indeterminate period of time. The infrastructure's current status has an effect on water access and water quality in the homes in Altamira, where lower socioeconomic households are shown to be affected more so than their socioeconomically better off neighbors.

The role of water and contaminants as a pathway for illneses in low socioeconomic populations needs to be further examined in Altamira. The small sample size should be expanded to perhaps explore the totality of the city's population. Further, in order to perform water quality analyses, the sample was biased to homes which possessed wells, even if these were not being used as a main source of water at the time of the study. Aware that generalizations are not to be made from this small sample, the data still presents important inclinations regarding the exposure to and ingestion of contaminants and socioeconomic level. Water access and quality seem to be more readily available for higher income homes which have sewage services and water treatment systems.

Implementation of basic sanitation services appropriate to public health and environmental protection are imperative in Altamira, yet national development priorities for the Amazonian region maintain their extractive history. At a regional scale, Altamira is no different than many other small cities hosting large development projects. Concerned with economic growth in the urban and industrial parts of the country, national decisions disregard the needs of the population in these forgotten places. In Altamira, Belo Monte's hydropower is diverted to industries and urban regions of Brazil, while the Amazon population remains with little voice. These communities face the severe impacts of population booms brought for by large developments which exploit the region and do not even offer adequate services to supply the basic sanitation needs of the population.

In order to provide a more accurate picture of the full impacts of large developments in the

Amazon and elsewhere, both social and environmental components need to be examined. This interdisciplinarity can yield a more robust representation and understanding of the challenges faced in our society, answering questions perhaps too broad or complex to be undertaken by a single discipline. The social elements discussed in this study are important variables that must be taken into consideration when examining water access, quality, and sanitation services in Altamira and many other communities where large projects are planned or being developed. Integrating multiple insights to construct a more comprehensive understanding of the problems faced in these regions can yield a more complete depiction of the true sacrifices and risks these communities face.

## CLOSING REMARKS

Energy assurance, water access, and water quality are inevitably intertwined in dam development through the water-energy nexus, an interlinkage that is evermore evident as numerous dams are planned throughout three of the world's most biodiverse basins: the Amazon, Congo, and Mekong. The development of large hydroelectric expansion in the Amazon, the world's vastest freshwater basin, brings about unprecedented consequences to the natural resources in that biome. The complexities of these unintended aftereffects to the most basic building block of life, water, cannot be fully understood if viewed through a single non-integrative perspective. With the goal of filling a gap in the current literature, this study draws on natural and social sciences, integrating their approaches to construct a more comprehensive understanding of the human environment interactions in water access and quality, particularly in sanitation. Considering sanitation both an important societal and environmental issue that affects environmental quality and human health, this study explores the consequences of major hydroelectric development projects to water and sanitation services in neighboring communities, ultimately exposing impacts to water resources in these areas. Using Belo Monte and Altamira as a model system, the results of this study can aid in the potential reduction of negative impacts resulting from hydroelectric development. The aim is to contribute to the literature that addresses approaches that seek to ensure availability of water and sanitation for all and potentially aid in avoiding future service provision deficiencies in cities affected by major hydroelectric development projects.

As more dams in the Amazon region are planned, identifying high-risk locations in dam hosting communities can be a first step in understanding the environmental variables at play. The first study of this dissertation developed a heuristic for discerning areas susceptible to groundwater and drinking water well contamination based on elevation, groundwater levels, and well and septic tank distances to rainfall induced flow paths and accumulation areas. Wells located in areas with shallower ground-to-water table depths, and areas within 76 meters of a flow path or a control-flooded area, are of particular importance. Altamira's city center is identified as a high-risk location for septic tank contaminant transport to drinking water wells. This area is at risk due to its high population density and relatively low elevation compared to other parts of the city, as it is often flooded during heavy rain events. An increased probability of infiltration of septic tank pollutants to the water table is observed in this area, along with the southwestern portion of urban Altamira, which puts the general groundwater quality of the city at risk. Areas with low elevations and dense proximity of households can become a focus of waterborne illnesses and should be prioritized in the implementation of a reliable water distribution network and adequate sanitation services. These areas should be the first ones to be considered when implementing measures to mitigate impacts of large hydroelectric projects. Preparing for the sudden population increase brought forth by large developments, and providing reliable water distribution and basic sanitation and sewer services, would reduce construction of new septic tanks and water wells. These results can guide implementation of public health and sanitation efforts in areas impacted by large hydroelectric projects to avoid, manage, and perhaps hinder future sanitation and water quality crises.

Aside from a spatial and geographical understanding of the areas at risk, public policy implementation plays a significant role in the resulting water quality, access, and sanitation of areas affected by major hydroelectric projects. The intricate relationships between political, social, and environmental elements influence the provision of water and sanitation services and, due to their importance and complexity, adequate implementation of water and sanitation policies requires understanding beyond environmental variables. Therefore, the second study in this dissertation identified gaps in the implementation of national water and sanitation policies and Altamira's current circumstances with regards to water access, water quality, and sanitation.

In the case of Belo Monte, it is evident that Brazilian energy production through hydropower was perceived as a greater national benefit and overpowered natural resource conservation at a regional level, quality of life at a local level, and the protection of water resources mandated by the legislation discussed in this work. Drawing from past experiences of large developments in the region, and long before dam construction begins, a comprehensive grasp of local sanitation practices, services provided, and hindrances in service provision is crucial in order to take appropriate actions in water and sanitation efforts. Moreover, accurate projections of the expected incoming population are desperately needed as well as clear and reliable communication of these numbers to local and state agencies. Understanding that exact numbers may be impossible to project, population estimations can be made from previous hydroelectric projects developed in the region which present ample evidence of the increases expected during the construction phase. This information can be used to better plan, prepare, and provide enough resources to cope with the sudden population increase in neighboring communities. Minimizing the impacts to drinking water resources and public health requires that adequate water distribution and sanitation networks are in place *before* any large hydroelectric projects begin to be constructed. Otherwise, the population suffers the unintended consequences of lack of water access, quality, and adequate sanitation services long after the construction ends. Further, attempting to implement national scale approaches without taking into account local and regional circumstances, and without ensuring a timely provision of funds at the right scale, prevents mechanisms of cooperation between different levels of government from functioning to benefit the population. In the case of Belo Monte, legal requirements regarding sanitation infrastructure were not provided in a timely manner, yet the project continued to be built and ultimately allowed to operate. This illustrates how current implementation of public policies and laws ignore the population most affected by the construction of large development projects in the Amazonian region. Hence, ensuring stern consequences at all levels of government for noncompliance with water and sanitation legislation is of utmost importance. Administering changes and providing adequate sanitation services, environmental protection, health promotion, and other social interests that result in improving the quality of life of the population is a long process that needs to begin long before a hydroelectric project commences. Identifying public policy implementation gaps that affect basic sanitation and water resources creates opportunities to anticipate problems that could impinge on the public health needs of residents where such large infrastructure projects will be implemented.

The lack of sufficient resources and appropriate implementation of a water and sewage network in Altamira *prior* to the arrival of Belo Monte led to an increase in the volume of septic tanks and drinking water wells. Serving as the main drinking water supply for residents not connected to water distribution services, the aquifer beneath Altamira received increased septic discharges in the form of fecal contaminants. In order to gain deeper understanding of the concentration and reach of these contaminants throughout the city, the third study in this dissertation employs biological methods and statistical analyses to determine relationships between fecal contaminant presence and concentration in wells, water table depth, and population density. Altamira's groundwater resources show the existence of fecal markers and human fecal contamination. Findings show that seasonality influences the presence and magnitude of contaminants found in wells. During the rainy season, when groundwater levels rise, *E.coli* increases its spatial reach and *B. theta* concentrations are amplified in the densest populated areas of the city. This revealed that, aside from seasonality and changes in groundwater depth, population density can become an important preliminary indicator of the potential magnitude of contaminants found in residential drinking water wells of cities impacted by large hydroelectric projects. This knowledge is crucial in developing strategies to tackle sanitation in areas that are most vulnerable to cross contamination from septic tanks to drinking water wells and yields a more comprehensive understanding of where efforts should be focused to ensure availability of water and sanitation for all.

While the spatial and temporal understanding of contaminant presence in the city is of great importance, socioeconomic variables play an equally significant role in the population's access to water, water quality, and sanitation services. In order to broaden the comprehension of risks within Altamira's population, the fourth study in this dissertation addresses contributing social variables. Exploring the importance of socioeconomic status in the exposure and ingestion of fecal contaminants provides a more nuanced awareness of the true risk encountered by households in communities facing hydroelectric expansion.

The water distribution in Altamira has been established longer than the sewage network. Connection to sewer services began in 2017 and, perhaps due to their recent development, these connections were less extensive in the lower socioeconomically ranked homes. Conversely, connection to water services did not display a clear relationship to socioeconomic level. Nonetheless, access to water and the irregularity of water distribution services is observed to affect lower socioeconomic homes more than others. This is most evident in the economic capital needed to dig a well in order to supplement irregular water services or the cost of digging an existing well deeper to ensure water during dry months. Pump maintenance, acquisition of storage tanks, or bribes to tank truck drivers are also factors affecting water access in lower socioeconomic households located in irregularly served areas of the city. Lower socioeconomic level households located in high elevation areas are particularly vulnerable to limitations in water access, as they may require deeper wells, which are priced by the meter and increase in cost with every meter dug to obtain access to water.

Because households of different socioeconomic levels coexist within the same block, contaminants from the septic tanks of homes not yet connected to sewer services can reach neighboring water wells irrespective of socioeconomic status. This makes the development of a global water and sewage network of particular importance for the conservation of water resources and preservation of water quality in the area. Norte Energia's initial underestimation of water consumption in the Amazonian region led to scarcity in water services, requiring expansions to the water treatment and distribution systems in place. System expansions have been slow, riddled with delays and design flaws. Similar hindrances are observed in sewage services where continuous litigation and hindrances in the connection of homes to the system aggravates groundwater quality in the city. Aside from access to water, socioeconomic scale plays a role in the ingestion of fecal contaminants present in Altamira's groundwater resources. While all socioeconomic levels can be at risk of exposure to fecal contaminants due to their use of the same water resource and proximity of residences irrespective of social class, not all are at equal risk of ingestion. The disposition to pay for in-home water treatment systems is dependent on a household's financial capabilities and the ease of use of these options, both important factors on the willingness to adopt water treatment technology. Homes of higher socioeconomic rank purchase or filter their drinking water and use in-home water treatment options more frequently, while lower socioeconomically ranked households do not treat their water as often and, when they do, use boiling and chlorination instead. Regardless, introduction of water treatment technology without consideration of the socio-cultural aspects of the community and without behavioral, motivational, educational, and participatory activities is unlikely to be sustainable at any level.

Aside from an adequate distribution and sewage network, initiatives in water, hygiene and sanitation must include community participation, education, and behavior modification.

It is necessary to continue examining the role of fecal contaminants in water resources as a pathway for illnesses in communities hosting large infrastructure development projects. The results of this work present important tendencies regarding exposure and ingestion of contaminants in these communities. In Altamira, water access and quality seem to be more readily available in higher socioeconomic level households, which have sewage services and in-house water treatment systems. This does not mean, however, that this population was unaffected. As previously discussed, the lack of sufficient water distribution and sanitation services impacted drinking water resources for the entire population. Observing Belo Monte and the continuous postponement of water and sewage service provision, it is clear that areas not connected under current efforts will remain without services for an indeterminate period of time. The lack of resources at a local level limits the expansion of services that can be provided to match the pace of population growth, deepening the implementation failures of basic sanitation services appropriate to public health and environmental protection.

This work sheds light at how national development priorities for the Amazonian region maintain their extractive history, rather than prioritizing its regional economic development and welfare. National decisions focus on the economic growth in urban and industrial parts of the country and disregard the basic needs of the population in these forgotten and distant places. In this sense, Altamira is no different from many other small cities hosting large development projects that exploit the region. Belo Monte's hydropower is diverted to industries and urban regions of Brazil, while the Amazon population remains underdeveloped and burdened with the repercussions. Communities hosting large development projects face the severe impacts of population booms and are not even offered adequate water and sewage services to meet their basic needs. In this sense, Belo Monte was a squandered opportunity to improve the quality of life in Altamira and surrounding communities. Instead, noncompliance with required permits, continuous litigation processes, inadequate resource allocation, and gaps in the implementation of legislation were a few of the causes that sabotaged the chances of providing appropriate services to Altamira to enhance the city's sustainable development. Although improvements to the water and sewage networks are underway, there is still much to be done in order to provide equal and just sanitation services to the totality of the population. Improving the sanitation systems in place and increasing the portion of the population served with adequate and safely managed services remains a goal yet to be attained in the case of Altamira and the Belo Monte project. Therefore, it is clear that sanitation and health challenges need to be addressed *prior* to the arrival of a dam to avoid future sanitation deficiencies in cities affected by major hydroelectric development projects.

In order to provide a more accurate picture of the full impacts of large developments in the Amazon and elsewhere, both social and environmental components need to be examined. This interdisciplinarity can yield a more robust representation and understanding of the challenges faced in these situations, answering questions perhaps too broad or complex to be undertaken by a single discipline. The social elements discussed in this study are important variables that must be taken into consideration when examining water access, quality, and sanitation services in Altamira and many other communities where large projects are planned or being developed. Integrating multiple insights to construct a more comprehensive understanding of the problems faced in these regions can yield a more complete depiction of the true sacrifices and risks these communities face.

The changing Amazonian demographic stemming from hydroelectric expansion creates impacts on water access, quality, and sanitation. Understanding the connections between social and environmental variables at play in these scenarios is imperative to avoid sanitation deficiencies in cities affected by major hydroelectric development projects. It is of great importance to draw from multiple disciplines to move forward in all sciences and create a path to deeper understating of our world, our place in it, and the outcomes of combined human-environment interactions through a more integrative scope. Appropriate sanitation is both a societal and environmental issue that affects water quality and public health. The information provided in this dissertation aims to improve understanding of the connections between social and environmental variables to potentially prevent or at the very least lessen future threats to water quality in regions where large infrastructure development projects will be implemented. The information provided can aid in the development of approaches that ensure availability of water and sanitation for all, and contributing to the necessity for the expansion of adequate and equitable access to safe drinking water.

While there has been great interest in the impacts caused by large dams, current academic literature has yet to touch upon the relation between population growth, socioeconomic disparities, water quality, and basic sanitation under the rapid changes brought forth by large hydroelectric projects. Bringing together natural and social sciences, in the context of a large infrastructure project, we view environmental and social factors as combined forces that impact public health through contaminant transport and water quality. The support of Michigan State University's tenured faculty, experts in the fields of geography, hydrogeology, water quality and public health, along with the cooperation of in-country universities, increases relevance and practicability of fieldwork and promotes collaboration between international institutions. Using approaches and techniques from different fields of study, this project serves as an example of convergent research that can advance work across disciplines and explore environmental and social impacts as intertwined outcomes of project development, not only in the Amazon region, but throughout the world.

Considering the growing role that hydropower plays in the sustainable energy portfolios of developing countries, the need to minimize environmental and social issues arising from hydroelectric expansion becomes imperative. This research explores the environmental and social processes impacting sanitation and that, if left unexplored, can continue to impinge on public safety by means of sanitary collapses in communities located upstream of hydroelectric projects. Understanding social and environmental interactions is crucial to the improvement of living conditions in communities affected by hydroelectric developments. Research results have practical applications that directly contribute to ensuring energy access to all, while preserving clean water and sanitation access to communities affected by hydroelectric projects. Relaying results to collaborating universities and local government can shed light on the sanitation practices and water quality concerns that continue to be unaddressed in the Amazon Basin and developing world. This project has developed enduring academic exchanges that add to the pursuit of partnerships and increases the relevance of research, benefiting society through the advancement of global health security, reduction of inequality, and increase in global cooperation.

# APPENDIX

# APPENDIX

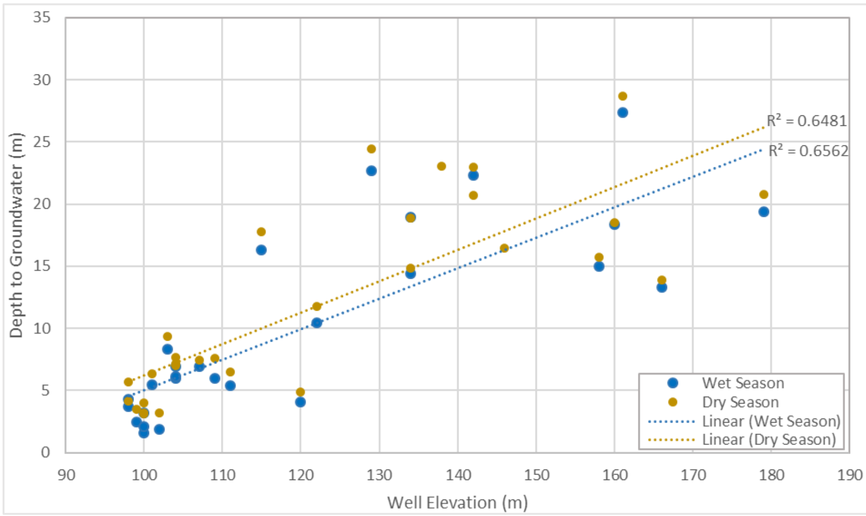


**Figure A.1:** Well elevation and depth to groundwater in sampled households

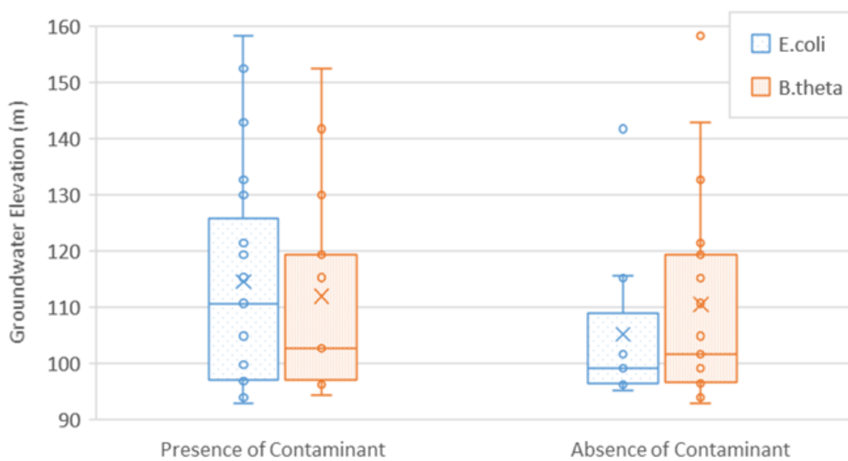


**Figure A.2:** Presence and absence of contaminants at varying elevations for the dry seasons

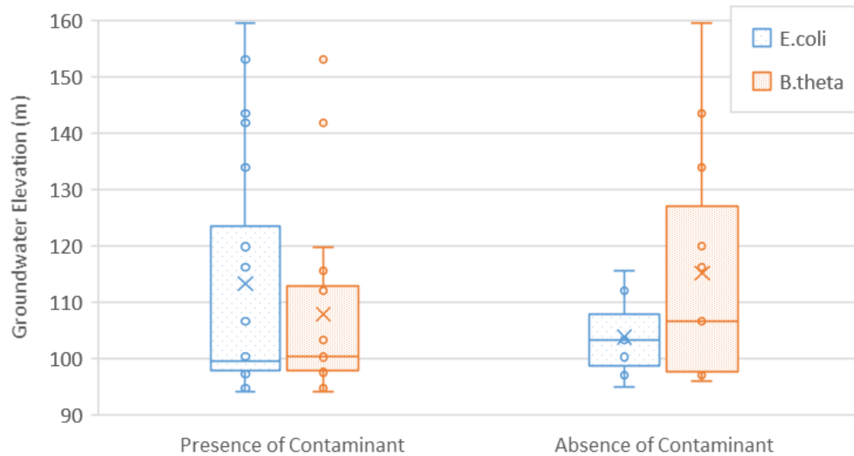


**Figure A.3:** Presence and absence of contaminants at varying elevations for the wet season

| | Groundwater Depth | | | Change in Groundwater | | |
|---|---|---|---|---|---|---|
| | S | p-value | rho | S | p-value | rho |
| *E.coli* Concentration | | | | | | |
| Dry Season | 2596.5 | 0.0201* | 0.4223* | 4014.9 | 0.2580 | -0.2255 |
| Wet Season | 2668.5 | 0.3544 | 0.1854 | 3633.8 | 0.5876 | -0.1092 |
| *B. theta* Concentration | | | | | | |
| Dry Season | 4098 | 0.6426 | 0.0883 | 3290.6 | 0.9824 | -0.0045 |
| Wet Season | 3243.4 | 0.9607 | 0.0099 | 4660.2 | 0.0281* | -0.4225 |

**Table A.1**: Correlation Results between Contaminant Concentrations, Groundwater Depths, and Change in Groundwater

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| ***E.coli*** | | |
| Dry Season | 0.199 | (-0.0118 - 0.0898) |
| Wet Season | 0.284 | (-0.0176 - 0.1206) |
| ***B.theta*** | 0.823 | (-0.0358 - 0.0445) |
| Dry Season | 0.823 | (-0.0358 - 0.0445) |
| Wet Season | 0.338 | (-0.0207 - 0.0651) |

*$*p \leq 0.05$, $** p \leq 0.01$, $*** p \leq 0.001$, $**** p \leq 0.0001$*

**Table A.2**: Bivariate Regressions for Groundwater Depth and Presence of Contaminants *(ref = Absence)*

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| ***E.coli* Concentrations** | | |
| Dry Season | 0.0015** | (0.3543 - 1.2458) |
| Wet Season | 0.669 | (-0.3709 - 0.5810) |
| ***B.theta* Concentrations** | | |
| Dry Season | 0.487 | (-41.0959 - 87.2324) |
| Wet Season | 0.077 | (-7.2604 - 234.074) |

*$*p \leq 0.05$, $** p \leq 0.01$, $*** p \leq 0.001$, $**** p \leq 0.0001$*

**Table A.3**: Generalized Linear Model Regressions for Groundwater Depth and Contaminant Concentrations

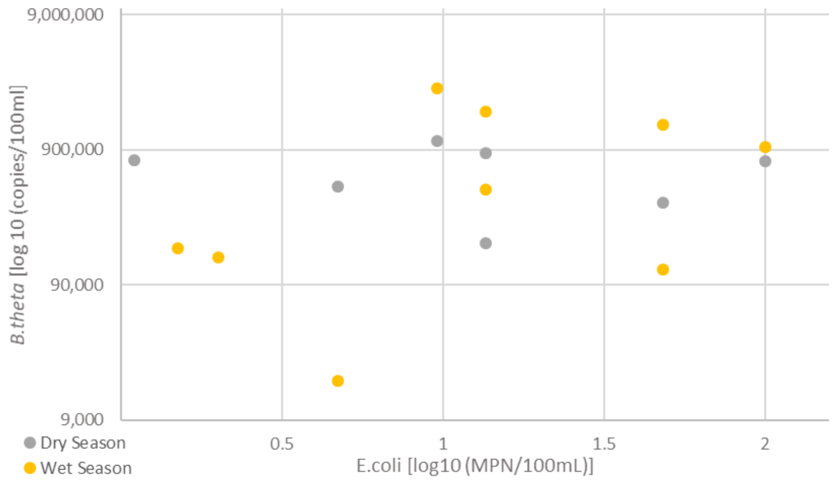


**Figure A.4:** *B. theta* versus *E. coli* concentration transformations
*(n = 30)*

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| **Log 10 *E.coli* Concentrations** | | |
| Dry Season | 0.0027 ** | (-2.3281 - 0.0816) |
| Wet Season | 0.323 | (-0.0061 - 0.0192) |
| **Log 10 *B.theta* Concentrations** | | |
| Dry Season | 0.718 | (-0.0100 - 0.0147) |
| Wet Season | 0.197 | (-0.0069 - 0.0407) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table A.4**: Generalized Linear Regressions of Groundwater Depth on Transformed Contaminant Concentrations

| | ***E.coli* Dry Season** | | ***E.coli* Wet Season** | | ***B.theta* Dry Season** | | ***B.theta* Wet Season** | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** |
| ***Population Density*** | | | | | | | | |
| Low | 0.084 | (0.0542 - 4.994) | 0.402 | (-2.5428 - 1.085) | 0.472 | (-2.3507 - 0.9915) | 0.804 | (-1.9665 - 1.4038) |
| Medium | 0.643 | (-1.8886 - 1.1749) | 0.485 | (-1.097 - 2.7369) | 0.880 | (-1.628 - 1.3671) | 0.009** | (0.6746 - 4.1904) |
| High | 0.168 | (-2.8327- 0.4680) | 0.925 | (-1.7043 - 2.1901) | 0.380 | (-0.8721 - 2.3542) | 0.993 | - |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table A.5**: Bivariate Regressions for Population Density and Presence of Contaminants
*(ref = Absence)*

| | ***E.coli* Dry Season** | | ***E.coli* Wet Season** | | ***B.theta* Dry Season** | | ***B.theta* Wet Season** | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** | **P(>\|z\|)** | **(95% CI)** |
| ***Population Density*** | | | | | | | | |
| Low | 0.562 | (-27.93 - 15.06) | 0.872 | (-23.52 - 19.90) | 0.685 | (-3153 - 2062) | 0.458 | (-6567 - 2922) |
| Medium | 0.210 | (-6.79 - 32.53) | 0.279 | (-31.08 - 8.69) | 0.0098 ** | (896 - 5231) | 0.285 | (-1948 - 6833) |
| High | 0.455 | (-29.68 - 13.14) | 0.185 | (-6.43 - 35.64) | 0.0213* | (-5331 - 580) | 0.694 | (-5748 - 3810) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table A.6**: Generalized Linear Regressions of Population Density and Contaminant Concentrations.

Low Socioeconomic Level: Unfinished walls and floors, low cost roofing materials (fiber cement), no domestic workers, motorbike or no transportation ownership, higher crowding proxy, receiving federal aid or having a low salaried member ratio .

Medium Socioeconomic Level: Finished walls and floors, roofing materials may vary, no domestic workers or once a week, motorbike or automobile ownership, mixed crowding proxy, no federal aid received, and having a low or mid salaried member ratio.

High Socioeconomic Level: Finished walls and floors, high cost roofing materials (roofing tile), domestic workers once or multiple times per week, automobile ownership or multiple motorbike and automobile ownership, low crowding proxy, no federal aid received, and having mid or high salaried member ratio.

**Table A.7**: Household Class Profiles

| Variable | Frequency (n) | Percent (%) |
|---|---|---|
| **Number of Residents** | | |
| 1 | 1 | 0.03 |
| 2 | 4 | 0.13 |
| 3 | 6 | 0.20 |
| 4 | 7 | 0.23 |
| 5 | 9 | 0.30 |
| 6 | 3 | 0.10 |
| **Number of Families** | | |
| 1 | 23 | 0.77 |
| 2 | 7 | 0.23 |
| **Number of Bathrooms** | | |
| 1 | 17 | 0.57 |
| 2 | 10 | 0.33 |
| 3+ | 3 | 0.10 |
| **Plastered Walls** | | |
| Yes | 22 | 0.73 |
| No | 8 | 0.27 |
| **Painted Homes** | | |
| Yes | 20 | 0.67 |
| No | 10 | 0.33 |
| **Tiled Floor** | | |
| Yes | 22 | 0.73 |
| No | 8 | 0.27 |
| **Roofing Material** | | |
| Tiled Roof | 4 | 0.13 |
| Fiber Cement | 26 | 0.87 |

| Variable | Frequency (n) | Percent (%) |
|---|---|---|
| **Receive Federal Aid** | | |
| Yes | 18 | 0.60 |
| No | 12 | 0.40 |
| **Employs Domestic Help** | | |
| Yes | 4 | 0.13 |
| No | 26 | 0.87 |
| **Connected to Water Network** | | |
| Yes | 9 | 0.30 |
| No | 21 | 0.70 |
| **Connected to Sewage Network** | | |
| Yes | 16 | 0.53 |
| No | 14 | 0.47 |
| **Working Residents** | | |
| 0 | 4 | 0.13 |
| 1 | 15 | 0.50 |
| 2 | 8 | 0.27 |
| 3 + | 3 | 0.10 |
| **Salaried Ratio** | | |
| 0 | 4 | 0.13 |
| 0.1 - 0.4 | 15 | 0.50 |
| 0.5 + | 11 | 0.37 |
| **Value of Transportation** | | |
| $0 - $999 | 6 | 0.20 |
| $1,000 - $5,000 | 11 | 0.37 |
| $5,001 - $14,999 | 7 | 0.23 |
| $15,000 + | 6 | 0.20 |

**Table A.8**: Descriptive Statistics of Socioeconomic Variables in Sampled Homes

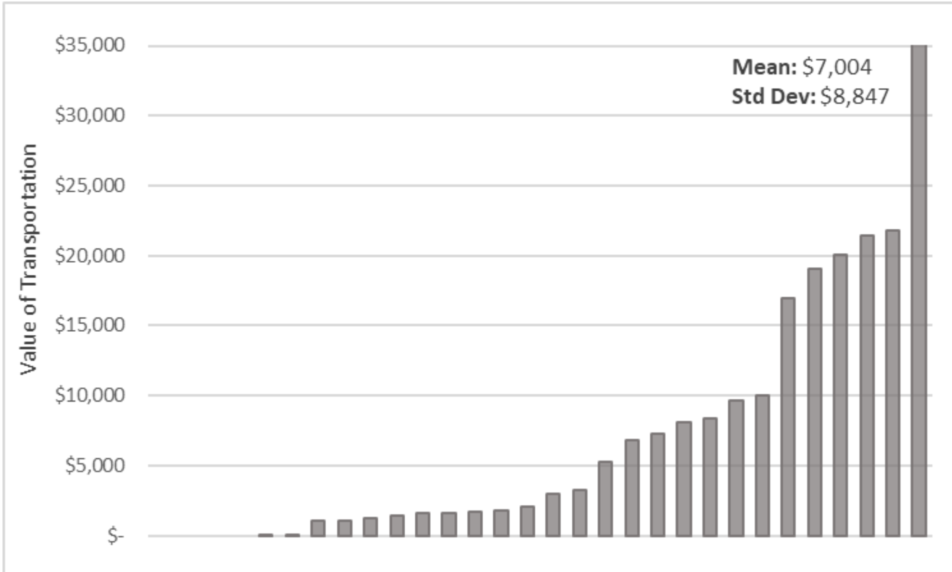


**Figure A.5:** Distribution, mean, and standard deviation for Value of Transportation in households sampled.

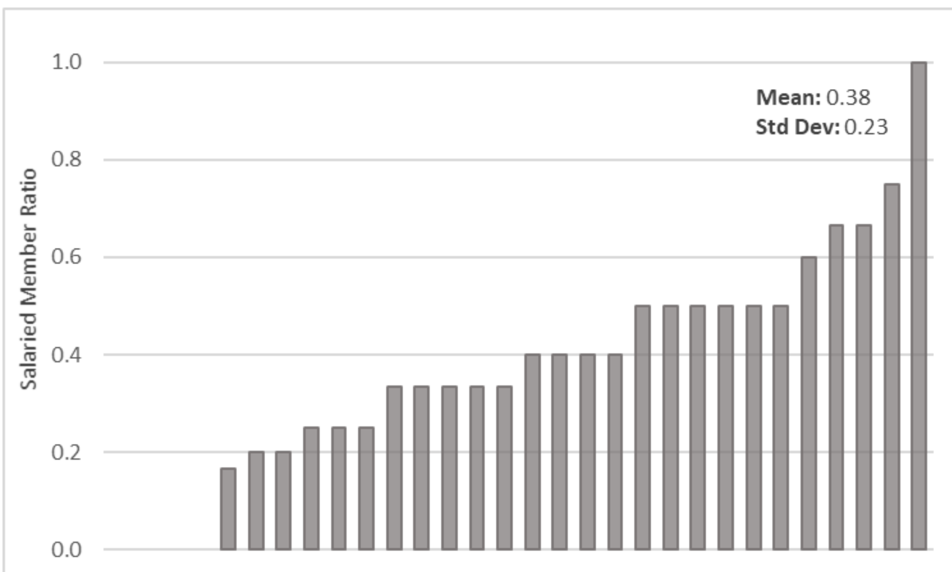


**Figure A.6:** Distribution, mean, and standard deviation for Salaried Member Ratio in households sampled.

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| **Number of Residents** | 0.9642 | (-0.760 - 0.796) |
| 1 - 2 | 0.781 | (-5.451 - 7.451) |
| 3 - 4 | 0.22 | (-1.073 - 5.311) |
| 5 - 6 | 0.664 | (-4.785 - 3.007) |
| **Number of families (ref = 1)** | | |
| 2 | 0.7914 | (-2.745 - 2.087) |
| **Number of Bathrooms** | 2.2e-06 *** | (1.4558 - 2.893) |
| 1 - 2 | 0.0002 *** | (1.803 - 4.726) |
| 3+ | 0.333 | (-0.066 - 1.066) |
| **Plastered Walls (ref = No)** | | |
| Yes | 0.0006 *** | (1.841 - 5.568) |
| **Painted Homes (ref = No)** | | |
| Yes | 0.003 ** | (1.258 - 4.942) |
| **Tiled Floor (ref = No)** | | |
| No | 0.002 ** | (1.414 - 5.314) |
| **Roofing Material (ref = Fiber Cement)** | | |
| Tiled Roof | 3.69e-05 *** | (3.310 - 7.729) |
| **Receive Federal Aid (ref = No)** | | |
| Yes | 0.0387 * | (-4.072 - -0.206) |
| **Employs Domestic Help (ref = No)** | | |
| Yes | 0.0001 *** | (2.927 - 7.535) |
| **Connected to Water Network (ref = No)** | | |
| Yes | 0.923 | (-2.344 - 2.121) |
| **Connected to Sewage Network (ref = No)** | | |
| Yes | 0.0195 * | (0.4906 - 4.2058) |
| **Working Residents** | 0.097 | (-0.131 - 2.003) |
| 1 - 2 | 0.507 | (-1.679 - 3.445) |
| 3 + | 0.454 | (-5.395 - 1.395) |
| **Salaried Ratio** | 0.139 | (-0.955 - 7.628) |
| 0.1 - 0.4 | 0.21 | (-31.614 - 6.174) |
| 0.5 + | 0.783 | (-11.841 - 8.849) |
| **Value of Transportation** | 1.35e-07 *** | (0.0002 - 0.0003) |
| $0 - $999 | 0.542 | (-0.0548 - 0.0270) |
| $1,000 - $5,000 | 0.310 | (-0.0012 - 0.0004) |
| $5,001 - $14,999 | 0.377 | (-0.0005 - 0.0016) |
| $15,000 + | 0.381 | (-0.0001 - 0.0004) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

**Table A.9:** Socioeconomic Scale Variables Regression Results

| Variable | P(>\|z\|) | (95% CI) |
|---|---|---|
| **Ingestion (ref = No)** | | |
| Yes | 0.057 | (-1.166 - -0.085) |

**p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, **** p ≤ 0.0001*

Note: Ingestion is Yes in homes with no water treatment, no purchase, and no connection to services.

**Table A.10:** Generalized Linear Model Regression for Socioeconomic Scale on Ingestion

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