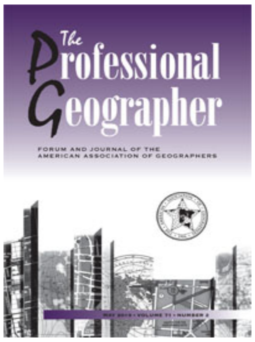

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Hydroelectric Infrastructure and Potential Groundwater Contamination in the Brazilian Amazon: Altamira and the Belo Monte Dam

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Heavy investments in hydroelectric development are occurring throughout the Amazon Basin, which holds 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 article 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 affected by large hydroelectric projects to avoid future water quality crises. **Key Words: Belo Monte, groundwater contamination, hydroelectric infrastructure, risk assessment, spatial and terrain analyses.**

水力发电建设的重大投资正在整个亚马逊流域展开，并涵盖巴西水力发电潜力的百分之四十二点二。贝罗蒙大坝是该区域中最新且最大型的计画。化粪池于亚马逊的盛行，加上水井的广泛使用以及大坝蓄水造成的地下水位上升，导致了上游社区的卫生与健康忧虑。我们运用空间分析数据和地物分析，指认贝尔蒙的所在城市阿尔塔米拉中，居住密度最高的邻里中的高风险地点。本研究的目的在于发展一个启发法，指认关乎既有和提案的水力发电计画而易受到地下水和水井污染影响的区域。阿尔塔米拉的市中心，由于人口密度与和相对城市其他地区而言较低的海拔，因此持续作为水井污染的高危险地区。本文所呈现的方法、工具及分析，提供了能够用来指认地下水与饮用水井污染的脆弱性之架构。 本文呈现的研究结果，能够指引在受到大型水力发电计画影响的地区实行公共健康与卫生的努力，以避免未来的水质危机。 **关键词：贝罗蒙，地下水污染，水力发电基础建设，风险评估，空间与地物分析。**

Grandes inversiones en desarrollo hidroeléctrico se están efectuando a través de toda la cuenca amazónica, para la cual se estima un 42.2 por ciento del potencial hidroeléctrico del Brasil. La presa de Belo Monte es el mayor y más reciente proyecto en esta región. La prevalencia de sistemas sépticos en la Amazonia, junto con el uso generalizado de pozos y la elevación del nivel freático por el llenado del embalse, crean preocupaciones sobre sanidad y la salud entre las comunidades situadas aguas arriba. Usando datos analíticos espaciales y análisis del terreno, identificamos localidades de alto riesgo dentro de los vecindarios más densamente poblados de Altamira, la ciudad anfitriona de Belo Monte. El propósito de esta investigación es desarrollar una heurística para identificar las áreas que son susceptibles de contaminación del agua subterránea y los pozos en relación con los proyectos hidroeléctricos existentes y propuestos. El centro de la ciudad de Altamira persiste como una localización de alto riesgo de contaminación de los pozos debido a la densidad de su población y a la elevación relativamente baja que tiene en comparación con otras partes de la ciudad. Los métodos, herramientas y análisis presentados en este artículo proveen un marco que puede usarse para identificar la vulnerabilidad a la contaminación de agua subterránea y el agua potable de pozos. Los resultados presentados aquí pueden guiar la implementación de esfuerzos en salud pública y sanidad en áreas afectadas por proyectos hidroeléctricos mayores, para evitar futuras crisis sobre la calidad del agua. **Palabras clave: análisis espacial y del terreno, Belo Monte, contaminación del agua subterránea, evaluación de riesgos, infraestructura hidroeléctrica.**

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's 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). Whereas 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

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capacity. A growing number of countries in Europe and North America remove dams each year, with approximately 800 dams removed in the United States alone from 1999 to 2016 ("Dams removed" 2016). In regions with lower levels of socioeconomic development, however, 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; Empresa de Pesquisa Energética do Brasil 2015). Given that the Amazon Basin holds 42.2 percent of Brazil's hydroelectric potential (Empresa de Pesquisa Energética do Brasil 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, US$1.7 billion; Jiraú, US$2.7 billion; and Belo Monte, US$6.3 billion; Luporini and Cruz 2015). The latter, Belo Monte, is the most recent and largest hydroelectric project investment in the region to date.

This article 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 might emerge, or already exist, as a result of large hydroelectric dam construction. The framework presented here can equip researchers and local governments with the 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.

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 made up of twenty-four turbines and twenty-eight 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 in hydroelectric potential (Agência Nacional de Águas 2013). This makes the area a prime location for the development of hydroelectric complexes. In the forty-five 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 twenty-four turbines by 2019 (Empresa Brasil de Comunicação 2016). Diverting 80 percent of the Xingú River's flow toward the turbines, the complex has the potential to generate an average of 11,233 MW per hour of operation, which will be distributed to seventeen 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 m above sea level.

The City of Altamira

Located 52 km upstream from the dam, the city of Altamira served as the main stage for the construction of Belo Monte (Figure 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

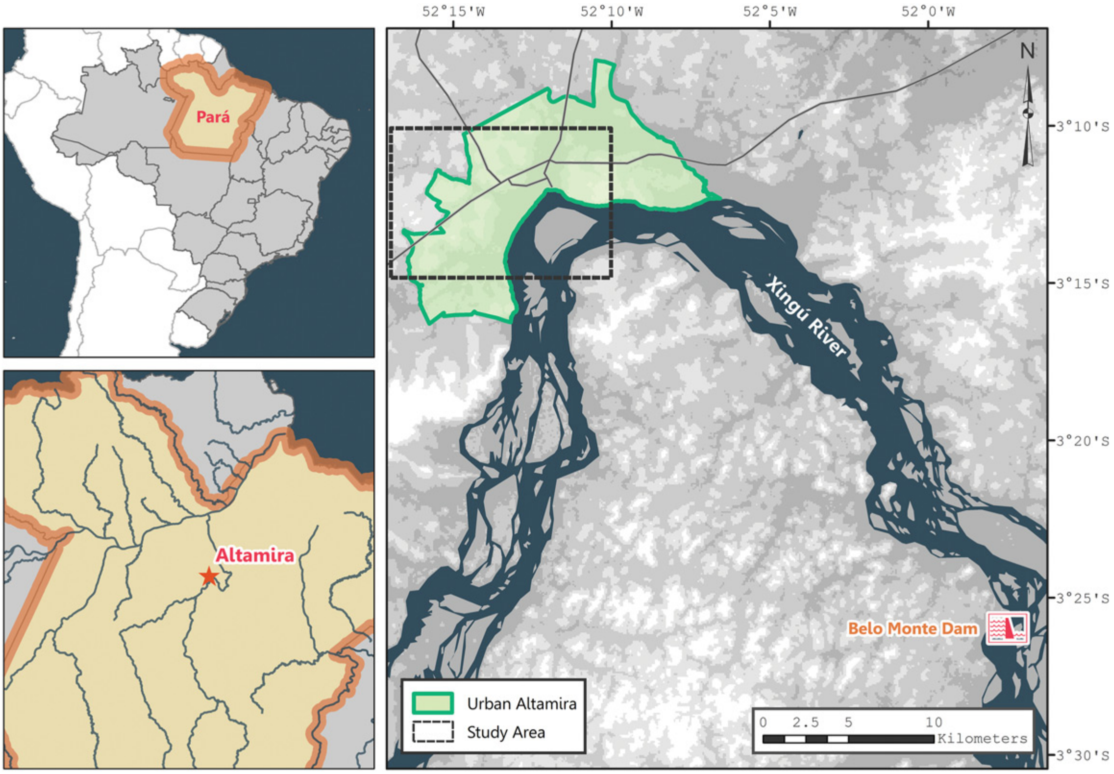

Figure 1 *Altamira, located along the Xingú River in the Brazilian Amazon Basin, Pará.*

temporarily settled in the area (Instituto Brasileiro de Geografia e Estatística [IBGE] 2011, 2016). Altamira's urban area now covers 112.9 km^2 and contains nineteen neighborhoods (IBGE 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 (IBGE 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.

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 2017 and Belo Monte's license to operate was suspended until the sanitation crisis was fully addressed (Ministerio Publico Federal 2016, 2017; Pessoa 2016).

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 (John and Rose 2005; De Roda Husman et al. 2009), 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-lying 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.

Surveyed Households and Monitoring Well Data

One hundred and thirty household surveys were conducted in the urban area of Altamira in July 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 thirteen most densely populated neighborhoods (out of nineteen) 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 six 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.

Semistructured interviews were performed in June and July 2016 with personnel from the following local offices and government branches: 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 (2016) online repository. Quarterly measurements from fifty-six monitoring wells in the region were gathered for the years between 2012 and 2015. Of these, forty monitoring wells were located within the urban area of Altamira.

Methods

The heuristic presented here identifies areas where drinking water wells might 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; National Aeronautics and Space Administration Land Processes and Distributed Active Archive Center [NASA LP DAAC] 2001), (2) calculating groundwater elevations at the monitoring wells using the digital elevation model (DEM) 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-lying 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-m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM V3; NASA LP DAAC 2001), obtained from the NASA Reverb | Echo repository, 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 (ArcGIS, Version 10.2, Esri, Redlands, CA, USA). 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 (ArcGIS, Version 10.3, Esri, Redlands, CA, USA). Using data from the forty 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 forty 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 DEM (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 DEM 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 U.S. Environmental Protection Agency (EPA) guidelines dictate that household drinking wells should be a minimum of 76 m away from streams and flooded areas to minimize contamination (EPA 2002a, 2002b). Household wells along this 76-m 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 m to streams and flooded areas. Flooded areas were predicted at 100 m above sea level by dam developers and Altamira's urban planning office. The 76-m 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 that can further threaten water quality in the area.

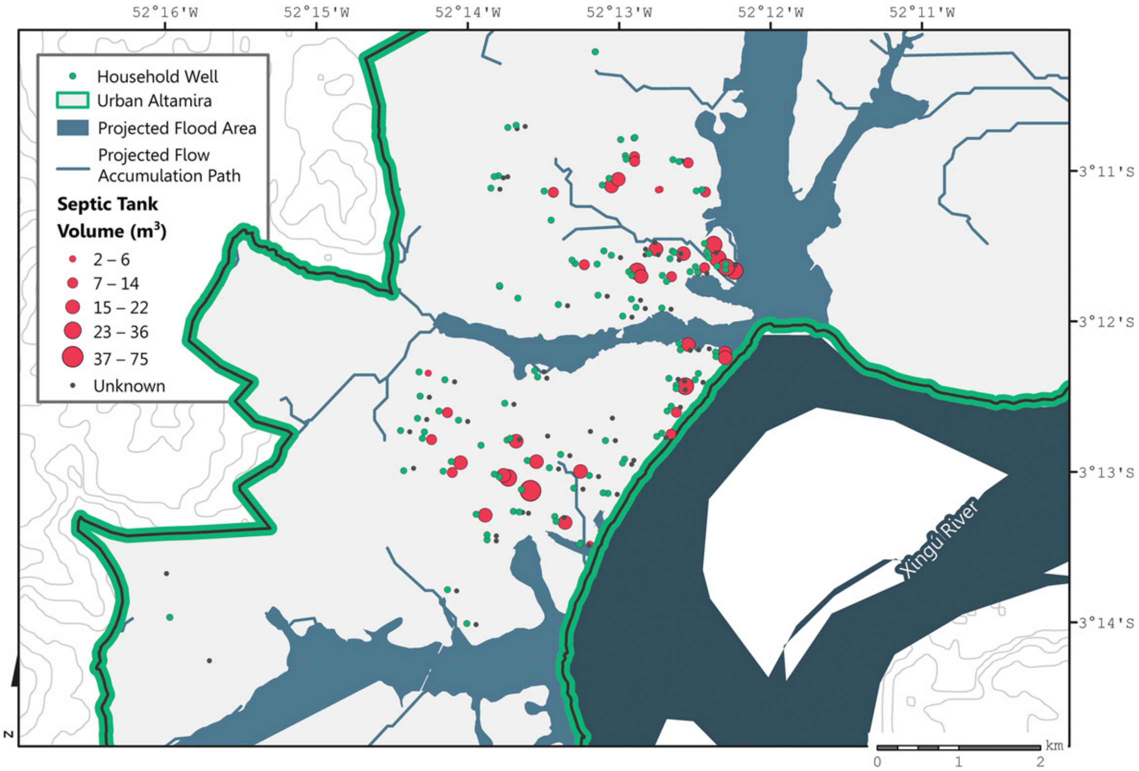

Figure 2 *Location of surveyed household wells, septic tanks, projected flow accumulation paths, and projected flood areas in urban Altamira. Projected flood area source: SEMAT (2016).*

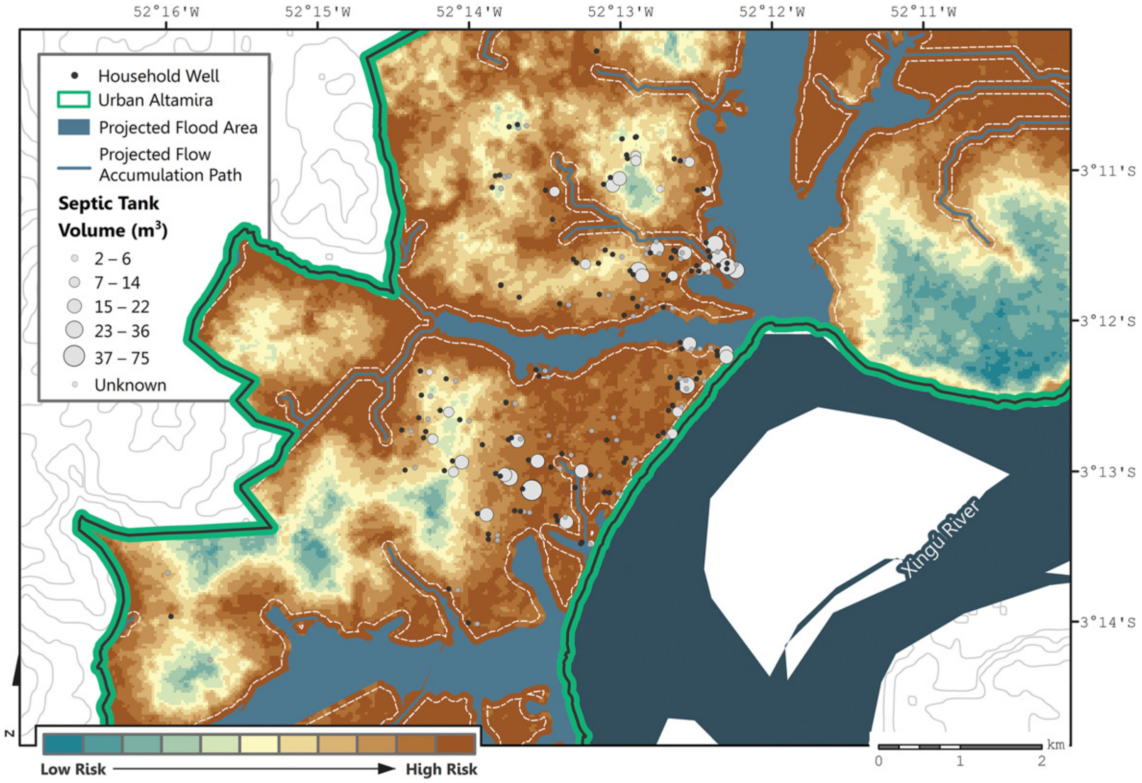

Figure 3 *Interpolated groundwater depths (based on nearest-to-surface wet season groundwater measurements from monitoring wells), control-flooded area, and projected flow accumulation. Projected flood area source: SEMAT (2016).*

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). 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). 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 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 m of flow paths are at higher risk of suffering pollutant entry from surface flow infiltration. Figure 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 m of control-flooded areas, located at an elevation of 100 m 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, but wells located in areas with shallower ground-to–water table depths and areas within 76 m 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 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.

Future studies could factor the elevation of septic tanks in relation to water wells to further explore contaminant transport between these systems. Due to the population boom that occurred in Altamira after the decadal census, however, 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 midterm census prevent them 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 might emerge as a result of large hydroelectric projects.

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 article 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 affected by large hydroelectric projects such as Belo Monte to avoid and manage future water quality crises. ■

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