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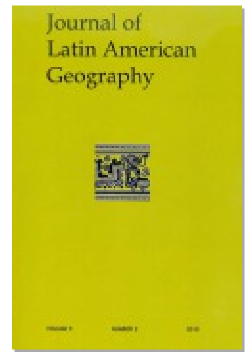

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Community Expansion and Infrastructure Development: Implications for Human Health and Environmental Quality in the Galápagos Islands of Ecuador

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Abstract
This study investigates the community of Puerto Villamil, located on Isabela Island in the western portion of the Galápagos archipelago. Urban development and human-environment interactions are examined through a geographic information science perspective by (1) constructing a time-series of aerial photographs and satellite images, (2) mapping the current water and sewage infrastructure in the community using GPS and digitized analog maps, (3) assessment of the current urban setting within the context of community growth, with special reference to water quality measures at locations within and adjacent to the community, interviews and focus group discussions with health officials and local residents about water-borne disease and human health, and an analysis of the proximity of the community and its water and sewage infrastructure to the surrounding environment.
Keywords: *Galápagos Islands, urban development, water and sanitation infrastructure, geographic information science.*

Resumen
Este estudio investiga la comunidad de Puerto Villamil ubicada en la Isla Isabela del archipiélago de los Galápagos. Se examina el desarrollo urbano y las interacciones humanas-ambientales a través de una perspectiva de la ciencia de información geográfica que incluye: (1) la construcción de una serie de tiempo de fotografías aéreas e imagenes satélites, (2) el mapeo de la infraestructura de agua y alcantarillado actual dentro el contexto del crecimiento comunal, con especial referencia a las medidas de la calidad del agua dentro y adyacente a la comunidad; el uso de grupos de discusión y entrevistas a oficiales de salud y residentes sobre las enfermedades trasmitidas por el agua y un análisis de la proximidad de la comunidad y sus infraestructuras al ambiente circundante.
Palabras clave: *Galápagos, desarrollo urbano, infraestructura de agua y sanidad, SIG*

Introduction

The Galápagos Islands of Ecuador are world-renowned. They are home to the Galápagos National Park and Marine Reserve, that have been declared a UNESCO World Heritage Site. These tropical oceanic islands have exceptionally high endemism of flora and fauna found nowhere else on the planet. Famed for the giant tortoises, marine iguanas, and the "Darwin finches", the Galápagos Islands maintain nearly 95 percent of the original native and endemic species that were present in the early 1500s when Europeans first reached the archipelago. Despite the Galápagos' portrayal in the media as "natural" and largely "pristine" and mostly free of humans, the archipelago is home to a growing permanent human population that is distributed across four populated islands. In addition, the Galápagos are being visited by an ever increasing number of international tourists who access the Galápagos National Park and Marine Reserve on cruise boats and through day-excursions from island hotels that reflect an expanded place-based recreation industry.

Sparsely populated from the time of their discovery through the early part of the 20th century, in the 1970s the Galápagos began to experience an influx of migrants from mainland Ecuador. Early inhabitants focused primarily on subsistence agriculture and fisheries, but they were quickly replaced by thousands of new residents who were attracted by the promise of lucrative opportunities in international fisheries, such as sea cucumber and spiny lobster (Bremner and Perez 2004, Kerr *et al.* 2004, Epler 2007). More recently, the growth of the international tourism industry in the Galápagos has driven immigration, particularly from the Ecuadorian mainland, by people seeking jobs in the tourism services sector and in associated support occupations, such as construction of hotels and related commercial enterprises.

Community growth and the expansion of the urban footprint in the Galápagos are now occurring at an accelerated pace in response to the rapidly growing tourism sector that drives the Galápagos economy (Epler 2007, Taylor *et al.* 2008). Efforts to control population growth and the rise in the number of visitors to the Galápagos were highlighted through the passage of the Special Regime Law for Galápagos in 1998 that placed restrictions on migration by essentially limiting residency in the islands to existing inhabitants at the time of the law's passage. Despite this effort, the local population of the Galápagos has continued to grow through the continued influx of permanent, temporary, and sometimes illegal immigrants to build and support the needs of the tourist industry, from nearly 10,000 in 1990, before the passage of the regulations, to more than 19,000 in 2006 (INEC 2002), eight years after the Special Law went into effect. It is widely believed, however, that the number of residents in the Galápagos now approaches 30,000, an under-count in the 2006 Census likely caused by the illegal status of residents and the type of census conducted, i.e., a *de jure* census that excluded people who were temporarily or illegally residing in the Galápagos at the time of data collection. Over the same period, the number of tourists has increased from 40,000 people visiting in 1990 to more than 173,000 in 2008 (GNPS 2009).

Associated with the expanded human imprint in the archipelago is the growing demand for consumer products, including food, bottled water, vehicles, building materials, and fuel. The exploitation of local natural resources, particularly in fisheries; and the generation of water, sewer, and sanitation problems related to the burgeoning human population (Buckalew *et al.* 1998, d'Ozouville 2008c) offer severe and persistent challenges to the complex interplay of resource conservation and economic development within a globally-important, protected area. For example, Santa Cruz Island, the most populated island in Galápagos with approximately 11,000 residents (INEC 2007a), serves as the hub of tourism in the archipelago, linking airplane service from the mainland with cruise ships and the increasing place-based recreation services. The urban port town of Puerto Ayora on Santa Cruz has grown dramatically in extent and density (Mena *et al*. 2008) with the addition of roads and vehicles to support transportation across the island (Villa 2008), increased construction of hotels and businesses aimed at tourists (Proaño and Epler 2008, Ordónez 2008), and homes and utility infrastructure to support the residents who are predominately engaged in tourism-based service occupations. In addition, six cargo ships are in perpetual motion from the mainland to deliver supplies to the Galápagos that range from basic food stuffs and water to sunscreen, batteries, building materials, and souvenirs. Over 30 flights per week bring visitors to the islands, creating a modern-day land bridge.

As a consequence of the increasing human footprint in the Galápagos, in June 2007 UNESCO added the archipelago to the list of World Heritage Sites "At Risk," citing illegal immigration and the resulting impact of population growth and development on biodiversity and invasive species, growth in the number of tourists, and inadequate regional planning among the threats to conservation of the Islands (UNESCO 2006). Similarly, in April 2007, the Ecuadorian government issued a Presidential decree declaring the Galápagos Islands in a state of risk and a national priority (Galapagos Conservancy 2007). In July 2010, UNESCO's World Heritage Committee voted to remove the Galapagos Islands from the list of sites endangered by environmental threats and overuse, stating that the Ecuadorian government had made significant progress addressing social and ecological threats to the Islands.

With the large increase in the overall number of tourists in the Galápagos Islands, the potential to develop a land-based rather than cruise-based tourism sector has led to substantial expansion of transportation and communication infrastructure to cater to tourists (Epler 2007). However, the same cannot be said of local utilities, including water and wastewater, sanitation, and electricity that have been largely ignored in this period of growth. At present, none of the four populated islands have working wastewater treatment plants, and there is concern that sewage is starting to pollute the ground water system and coastal environments that are near and down-stream of discharge points (Gelin and Gravez 2002, d'Ozouville 2008a). Further, there are apparently no concrete plans to build water and wastewater treatment systems in the near future, and thus the expectation is that there will be an increase in diarrheal and associated diseases, especially in infants, children, the elderly, and the poor, with likely extension to tourists. As such, gastro-intestinal ailments are common, and acute diarrheal diseases are the second most frequent cause of morbidity in the Galápagos (MSP 2007), although reporting of these conditions to public health practitioners is rare and there is almost no data available to know the true severity of the problem.

The goal of this study is to describe the space-time patterns of urban growth and the urban infrastructure through an integrated GIS and remote sensing perspective. Particular attention is paid to (1) the spatial organization of the water, sewer, and sanitation system in the community; (2) the porous volcanic landscape in which ground water is extracted for human use and waste-water is injected into the geological fractures as part of the community's water, sewer and sanitation system; (3) a growing local population that is placing increasing pressure on the limited urban infrastructure; (4) a community development plan that calls for a greater reliance on tourism and associated services to meet local employment needs; and (5) the juxtaposition of the community and the adjacent protected areas of the Galápagos National Park & Marine Reserve that are managed for resource conservation, but increasingly used for local tourism. To address these factors, the project tracks changes in Puerto Villamil, a community poised for economic development and meant to attract an increasing share of the international tourism market in the Galápagos. The study also examines the primary health problems in the community that are associated with water, sewer, and sanitations problems, including gastro-intestinal problems, fungal skin infections, parasites, and vaginal and urinary tract infections. Also assessed is the potential for significant environmental degradation on Isabela Island caused by water contamination of sensitive wetlands and lagoons, as well as a reduction in the amount of water available to support human and ecological needs. We use a mixed methods approach to assess population-environment interactions. The approach relies on a spatial data infrastructure that is framed within a GIS environment. To support our project goals, we have assembled airborne and satellite image time-series, conducted interviews with parents, children, health care professionals, and community engineers, and developed GIS data layers and analyses of the urban infrastructure, i.e., water and sewer lines, location of water injection points and water supply wells, building locations, and the pattern of the urban infrastructure, relative to human health outcomes, and the potential for anthropogenic threats to degrade a World Heritage Site.

Study Area: Puerto Villamil, Isabela Island, Ecuador

Located in the western portion of the Galápagos archipelago, Isabela Island is the largest (by area) and one of the youngest islands in the Galápagos. When the Galápagos National Park was established in 1959, existing settlements were excluded from the protected area and were instead designated for continued human use. Approximately 97 percent of the entire Galápagos archipelago is designated as a protected area of the Galápagos National Park, while the remaining 3 percent is reserved for human use. Isabela Island includes two spatially distinct human use zones – a rural community situated in the humid highlands along the flanks of Sierra Negra Volcano, and the town of Puerto Villamil, located in the coastal lowlands (Figure 1).

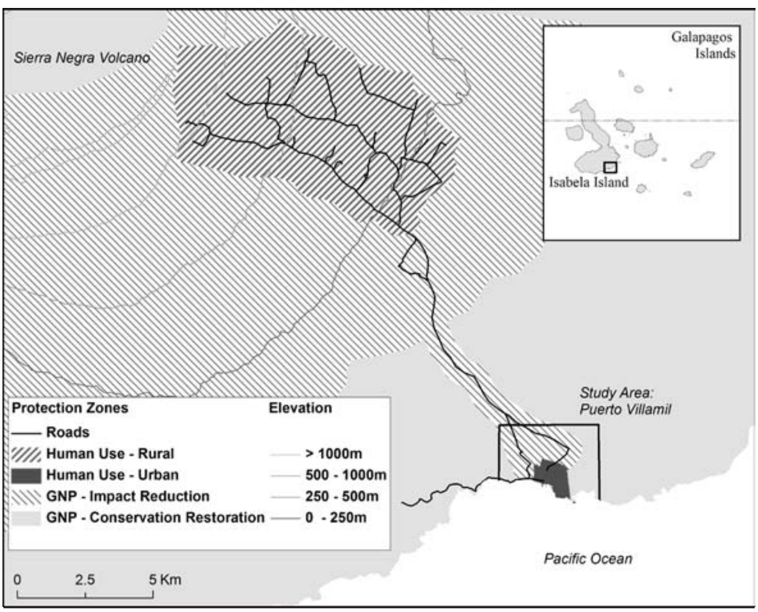

Figure 1. The study area of Puerto Villamil on Isabela Island.

Puerto Villamil is home to approximately 1,800 permanent residents who make up over 88-percent of the total population of the island (INEC 2007b). The residents of Isabela Island historically derived their livelihoods from agriculture in the humid highlands and fisheries along the coast (Proano and Epler 2008), although this has become less of the case as occupations have become more diversified and focused on tourism and service activities in and around the coastal town of Puerto Villamil. In recent years, Puerto Villamil has labored to increase its share of tourism by making the town more attractive to potential visitors through expansion of the local airport, construction of new hotels and restaurants, renovation of the existing dock facilities to better accommodate small tour boats, and the development of attractions and visitor sites within the town's boundary. The town's unofficial motto, "*Isabela crece por ti*," (Isabela is growing for you) highlights the desire for economic development by some local stakeholders as the path towards community sustainability.

Among the problems facing the inhabitants of and visitors to Isabela Island, and the Galápagos more generally, is the inadequate quantity and poor quality of fresh water and the lack of wastewater treatment and sanitation facilities throughout the archipelago. Although the archipelago is situated along the Equator, the Galápagos suffer from the scarcity of freshwater that varies in abundance from the arid and semi-arid coastal lowlands to the more humid highlands. A recent survey of citizen attitudes on the role of science in the Galápagos indicates the pronounced need for greater attention to health and sanitation (Quiroga and Ospina 2009). Yet despite the growth in some aspects of urban infrastructure, the local water, sewer, and sanitation system of Isabela Island has not been appropriately planned or improved to meet the demands of a growing population and the increasing numbers of visitors.

Background and Context

By far, tourism drives development in the Galápagos (Epler 2007, Taylor *et al.* 2008). The agricultural and fisheries sectors are dwarfed by the increasing number of residents and visitors to the islands, and the corresponding amount of US dollars that encourage development. Population immigration from the Ecuadorian mainland, often illegal, occurs in response to the many "push" factors associated with a poor economy and the "pull" factors of real and perceived opportunities to improve the quality of life of individuals, as well as family members remaining on the mainland. This increased human dimension in the Galápagos, and the direct and indirect consequences of tourism and population migration are seen as a general threat to the conservation goals of the Galápagos National Park and to UNESCO's designation of the islands as a World Heritage Site (González *et al.* 2008).

Drawing from recent work conducted in Puerto Villamil, we examine community growth seen through the increased densification of dwelling units and public and commercial structures through an in-filling process that is designed to accommodate a growing local population who are settling in the community with the hope of new jobs and new lives. The human imprint is also expanding through the tourism industry that seeks to capture (and market) all that is special about the Galápagos. Constrained by the surrounding Galápagos National Park and Marine Reserve, Puerto Villamil has extremely limited opportunities for areal expansion, instead increasing the density of urban structures. Unfortunately, the expansion of the urban infrastructure has not accompanied urban development. The result is the continued dumping of water-waste directly into the ocean, and albeit at a reduced level, injection of waste into the fractured and porous volcanic geology that forms the island, and the importation of drinking water from the mainland, to augment small-scale, private processing plants. As a consequence, human illnesses and diseases continue to accompany the failure to expand urban services, with implications for people and the environment. The case study of Puerto Villamil is not an extreme one or an unrepresentative one, as all the communities in the Galápagos have been historically (e.g., Trac 1985, INGALA *et al.* 1989) and continue to be challenged by the general lack of high-quality and abundant fresh water and appropriate sewer and sanitation infrastructure (*El Colono* 2008, d'Ozouville 2008) that help insure human health and ecological integrity in the face of an ever expanding human imprint.

Data and Analysis

In this study, we draw upon a variety of spatially-explicit environmental, infrastructure, and social data to characterize urban development in Puerto Villamil between 1960 and 2009, with particular attention paid to community expansion and infrastructure development. Our data set includes: high-spatial resolution QuickBird satellite images acquired in 2003 and 2008; panchromatic and color aerial photographs acquired in 1960, 1992, and 2007; GIS layers of roads, water lines, and sewer lines in vector format; GPS locations (and attributes) of urban structures and water/sewer features collected in 2009; and statistics on household access to water and sewer systems that are drawn from the Special Census of the Galápagos Islands conducted in 2006. Additionally, our data set includes interviews that we conducted with local health practitioners, a provincial health official, community members, and the municipality of Puerto Villamil, that address issues of water, health, and environment on Isabela Island. The details of each data set and the associated analysis steps are described below.

Survey of Urban Structures and Infrastructure

During the summer of 2009, we conducted a census of urban structures and infrastructure in Puerto Villamil. All buildings and water infrastructure were mapped using Global Positioning System (GPS) units (Trimble GeoXT), and all GPS data were differentially-corrected using a local base station to an accuracy of less than 1.5-meters. A minimum of 180 points were collected for each feature location. For each structure, attributes were recorded including building types (e.g., dwelling, commercial, government, etc.); occupation status (i.e., occupied, abandoned, and under construction); number of stories; total number of structures (i.e., multi-building sites such as hotels); a general description of the structure (e.g., name of business or government agency); and whether an external water storage tank was present. The location of water and wastewater infrastructure included wells used to extract tap water for the community, the defunct water treatment facility, and piped-outflow points that carry water and waste into the ocean or that flow into fissures in the volcanic rock were also mapped. Finally, the position of the landfill and road network of Puerto Villamil were located and mapped. The data were cleaned for consistency and individual vector layers (point, line, and polygon) were created in ESRI ArcGIS 9.3 to produce a geographic database of layers, or shapefiles, for buildings, water/wastewater infrastructure, sites of special interest (e.g., the landfill), and the road network.

Time-Series of Urban Change

To examine spatio-temporal patterns of urban development in Puerto Villamil between 1960 and 2009, we combined data from our 2009 census of urban structures and infrastructure with very high resolution satellite imagery and aerial photographs to track the presence of individual buildings and road features. A 2008 QuickBird satellite image acquired over the study area was geometrically corrected (RMSE of 6.48 meters, achieved by using 24 control points and a 4th order polynomial transformation) using road intersections, corners of large structures, and other recognizable man-made features as control points. An acquired 2003 QuickBird satellite image for the study areas was geometrically referenced to the 2008 QuickBird image (RMSE of 2.62 meters, achieved by using 24 control points and a 2nd order polynomial transformation). Panchromatic and natural color aerial photographs of the region collected in 1960, 1992, and 2007 were scan-digitized, and geometrically registered to the QuickBird images for the analysis of urban growth.

Starting with the 1:30,000-base scale, natural color aerial photography, collected in 2007, the geo-referenced images were related to the point file of the 2009 building census and manually edited in the GIS to reflect the urban structures present in 2007 (each building was attributed by the date it first appeared on the image time-series). The updated 2007 building points were combined with the 2003 imagery and edited within the GIS to produce the 2003 building points; this process was repeated to include the 1960 image. A similar method was used to track changes in roads over time in which the road network, mapped in the field in 2009, was manually edited to reflect roads visible in the older imagery. The results of these analyses were reflected in individual GIS layers that showed the presence of buildings and roads in 1960, 1992, 2003, 2007, and 2009. Buildings and other man-made features could be clearly identified in all aerial photographs, though a set of aerial photographs from 1985 was excluded from this analysis due coarse grain-size.

To assess the nature of urban change, the following metrics of urban development were selected for analysis: (1) urban extent, (2) building density, (3) road length, and (4) road density. To measure and track these metrics over time, a consistent unit of analysis was needed, as the scale of the imagery varied among the multiple dates of the aerial photography, satellite imagery, and ground control. Since data on the legal boundary of Puerto Villamil were unavailable for all analysis periods and changes in the locations of roads and buildings, a grid of 1 hectare cells was used as the unit of analysis. For each time period (1960, 1992, 2003, 2007, and 2009), the urban extent was calculated in the GIS by counting the number of cells with at least one building present. Building density for each time period was determined in a similar fashion within the GIS by summing the number of buildings present (in a given year) within each 1 hectare grid cell. Because of limitations in the stereoscopic coverage of the historical aerial photography, building heights (or the number of stories) were not derived for the historical periods of the assembled image time-series). To visualize urban development over time, the five building density grids were mapped with the roads network superimposed. The final two measures of urban development, road length and density, were quantified for each time period to track changes in the urban road network. Road length was calculated as the total length of all roads within the urban extent, and road density as the length of roads in a particular year divided by the area of the urban extent.

Water and Sewer Infrastructure

Water and wastewater infrastructure on Isabela Island were mapped in a GIS using a combination of data from the urban structures and infrastructure survey, discussions with four community engineers, and digitized analog maps to assess the current state of water and sewer infrastructure for Isabela, particularly the spatial distribution of these utilities. Puerto Villamil engineers, responsible for the water, wastewater, and sanitation systems, were interviewed to understand how the public water and sewer systems function. They described the associated community infrastructure, spatial patterns of household (and government and commercial buildings) access to the piped water and sewer system, and methods to improve the current urban infrastructure. As part of the aforementioned survey of urban structures and infrastructure conducted by the research team during the summer of 2009, the location and associated attributes of water and wastewater features including wells, the defunct water treatment facility, and piped-outflow points that dispose of waste were located with the assistance of the municipal engineers and their positions were recorded using GPS receivers and also differentially-corrected. A GIS layer containing the GPS point locations of these features was created.

To capture underground infrastructure, analog maps of the water and sewer lines were scan-digitized, spatially rectified to be coincident with the other spatial data, and transformed from analog to digital format. However, the resulting GIS vector layers (polylines) represented only the main water and sewer lines, as maps of service pipes to specific buildings from the main trunk lines were not available. To determine which urban structures had the "potential" for sewer access, a 60-meter buffer was created around the existing main trunk lines, and structures and buildings from our 2009 survey, coincident with the buffer, were assigned an attribute to designate their "likely" access. The 60 meter dimension is a standard maximum distance between a sewer main and service points in the U.S., and empirical evidence suggests its applicability to Puerto Villamil.

The potential for water access was assigned by visual interpretation of neighborhoods, following discussions with the municipal engineers. Discussions indicated the areas that were included in the piped water system. Buildings within neighborhoods, known to have access to piped water, were assigned an attribute to represent "likely" water access. These estimates of water access were stratified by building type. The total number of residential dwelling units with water and sewer access in Puerto Villamil was calculated and compared to statistics that were reported on water and wastewater access in the community in the 2006 Special Census of the Galápagos Islands. The results of the spatial analyses of water and sewer access in Puerto Villamil were mapped, with the known and "likely" water and sewer infrastructure overlaid for reference.

Community Data Collection and Analysis

Interviews with six local and provincial health professionals in the community were conducted to examine water and sanitation problems in Puerto Villamil and their likely links to local residents' health outcomes, particularly, diarrheal diseases. In addition, two focus group interviews were conducted with six community members to further assess likely connections between water and sanitation and human health. With the aid of a field assistant from the local community, the interviews with the health professionals were conducted in Spanish and notes from the discussions were transcribed into English, while the entirety of the focus group interviews (also conducted in Spanish) were recorded and transcribed into English for subsequent analysis.

With local healthcare practitioners, questions were asked about the severity of the water problem in Puerto Villamil; general health problems due to water quality issues; age groups most susceptible to the health affects attributed to poor water quality in the community; type of medical treatments sought by residents and visitors to the community; and suggestions for potential solutions. With local residents, i.e., women and family members, questions were also asked about the age groups most affected by the inadequate water, sewer, and sanitation system; medical treatments sought, including home care remedies; preventative measures taken by members of the household; and suggestions for improving human health in the community.

Provincial-level healthcare professionals were also interviewed with the goal of understanding the general health concerns in the Galápagos, with an emphasis on Isabela and the community of Puerto Villamil. Questions centered on the severity of the water, sewer, and sanitation problem in the community, and more generally throughout the islands; populations that are most affected by water-related problems; medical treatments sought by residents and visitors; and suggestions for potential solutions.

Ancillary Data

Water quality statistics for Puerto Villamil were consolidated from data in annual water quality monitoring reports jointly published in 2007 and 2008 by the Galápagos National Park (PNG) and the Japanese International Cooperation Agency (JICA) (López Medina *et al.* 2007, López Medina *et al.* 2008), and results from an environmental impact assessment in 2009 that was conducted by the Universidad San Francisco de Quito (Valarezo Peña 2009). For all three studies, water samples were collected from various sites distributed around the community, including the tap water wells that service Puerto Villamil, lagoons and wetlands near community homes, wastewater disposal sites, and randomly selected homes where tap water was sampled. The water samples were analyzed for parameters including salinity, dissolved oxygen, total phosphorous, nitrates and nitrites, and fecal coliform. Data from these reports were compiled into a spreadsheet for this study and linked to their spatial locations using the GIS data layers.

Results and Discussion

Spatial-Temporal Patterns of Urban Development

Significantly influenced by rules and regulations developed by and for the Galápagos National Park and INGALA (National Institute for the Galápagos Islands, the former provincial authority in the Galápagos that regulated an assortment of development issues), the community does not "freely" expand even within its prescribed boundaries. For instance, mangrove forests are protected by law and so community expansion into such areas is substantially influenced by the Park and INGALA. Also, the geological structure of the area and the arid to semi-arid conditions necessitate government participation in "opening" new areas for development including the development of roads and the provision of electricity, water, sewer, and sanitation.

Our survey of urban structures and infrastructure shows that as of 2009, there were 837 buildings in Puerto Villamil (Figure 2) that are located within an extent of 115 hectares (Table 1). Single- and multi-family housing (and associated structures such as storage sheds, latrines, and garages) make up the majority of these structures (n = 536), and approximately 22 percent of these dwelling units also function as businesses (e.g., hotel/hostel, restaurant, laundry, pharmacy, tourism service, etc.). The buildings are clustered into 10 neighborhoods, with the oldest and densest development occurring in the central portion of the community. Road development has extended to many of the parcels in the *Pedregal 1* & *Pedregal 2* neighborhoods, located to the north of Puerto Villamil, and building density has increased as empty parcels have been developed for homes and industrial uses. Urban in-filling and increased densification of urban structures are likely to continue as the boundary of the community is rigidly prescribed by the surrounding Galápagos National Park and remaining undeveloped parcels are exceedingly few in number. Additionally, land along the beach road, located to the west of Puerto Villamil, has recently been developed to serve the tourism industry as is evidenced by an increase in the number and size of new hotels.

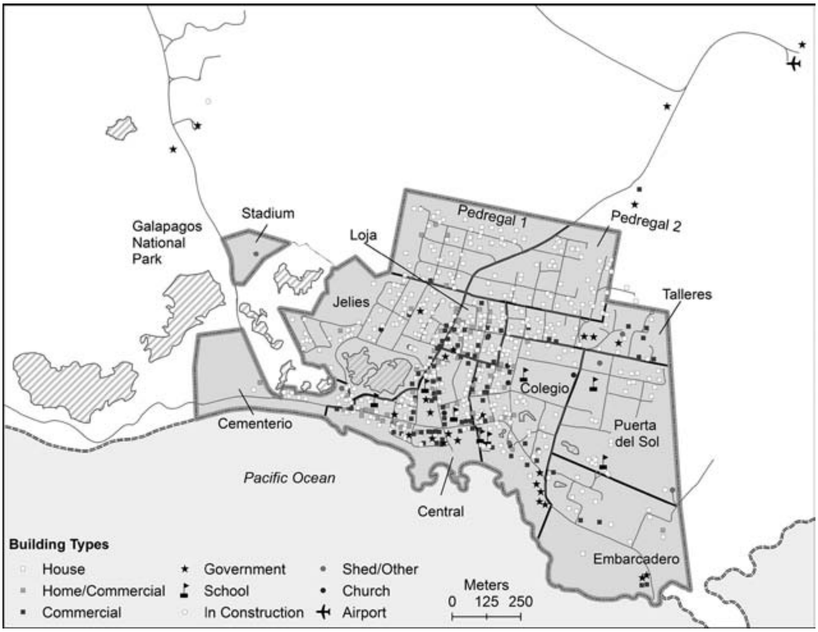

Figure 2. Buildings in Puerto Villamil, Isabela Island, 2009.

Table 1. Building and road density in Puerto Villamil, Isabela Island from 1960 - 2009.

		Building Density (#/ha)			Roads	
Year	Extent Area (ha)	Mean	Median	Max	Length(m)	Density (m/ha)
1960	12	3.0	3	5	1440	120.00
1992	42	5.4	4	14	5901	140.50
2003	86	5.8	2	22	14589	169.64
2007	103	5.7	3	24	18200	176.70
2009	115	5.7	4	24	19138	166.42

The town of Puerto Villamil has undergone significant periods of expansion and densification in the last 50 years that has led to the current pattern of development. From 1960 to 1992, Puerto Villamil transformed from a tiny fishing village into a small community as the extent of the community more than tripled and mean building density increased by nearly 50 percent (Figure 3a, and Table 1). A municipal government center developed near the beach with an associated commercial district that represented the highest building density during that time period (Figure 3b). The road that connects the town with the agricultural zone in the highlands was improved for vehicular traffic, at the same time road length within the extent of the community quadrupled, although road density only slightly increased.

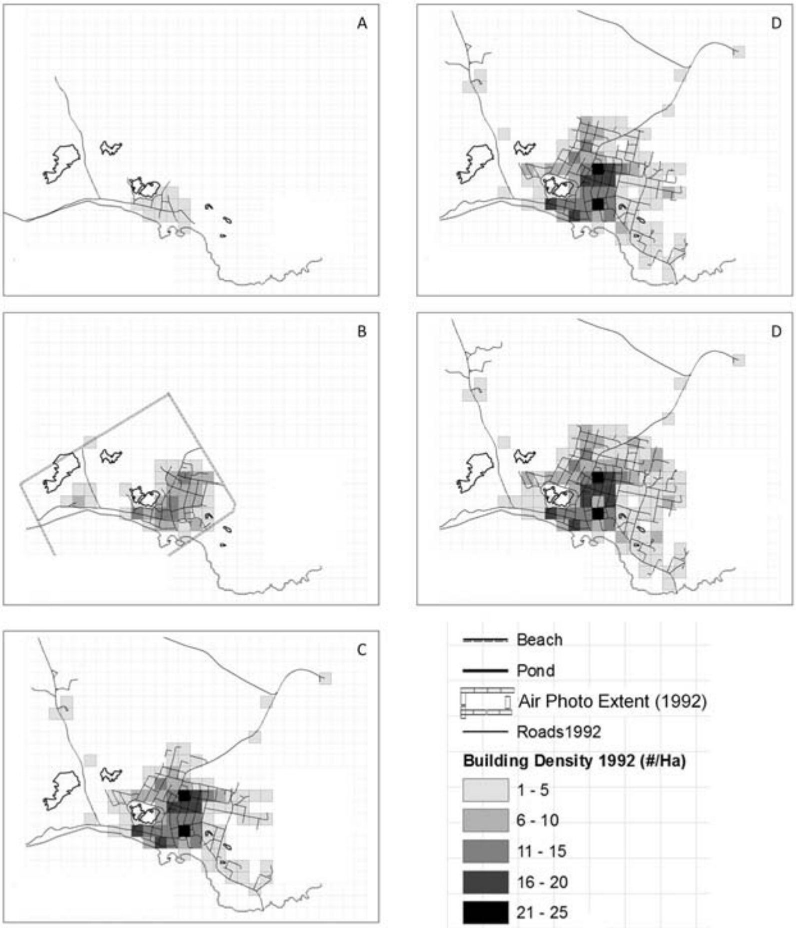

Figure 3. Building density and road networks for Puerto Villamil, Isabela Island, for 1960, 1992, 2003, 2007, and 2009.

By 2003, the community was better connected to the rest of the archipelago by a new airport (located northeast of the town center) and enhanced port facilities (located southeast of the town center) (Figure 3c). A new commercial center developed further inland to the north of the municipal town center that rivals the municipal town center for maximum building density. While the mean building density only increased slightly from the in-filling of the commercial center, the median density decreased substantially from 1992 to 2003 (Table 1), as low density development occurred along new roads connecting the town to the aforementioned transportation hubs, and road length within the extent of building development more than double from 1992. Furthermore, during this period several of the small lagoons located along the coast of Puerto Villamil were completely engulfed by development, and several lagoons even disappeared between 1960 and 2003 as they became cutoff from the ocean by development and were not able to survive without their replenishment during high tide (Valarezo Peña 2009).

After 2003, the expansion of the community into the lava fields on the north side of Puerto Villamil occurred (Figure 3d & 3e). Expansion of the community is significantly influenced by rules and regulations (e.g., nearness to mangrove forest and placement of structures on land parcels, particularly, in newly developed areas) developed by the Galápagos National Park and INGALA. Thus, the community does not "freely" expand, but grows within strictly defined boundaries that were established when the Park was created in 1959. However, some exceptions to these boundaries have been made in recent years, such as in the cases of the neighborhoods of Pedregal 1 and 2, where ecologically valuable land belonging to the municipality was traded to the Galápagos National Park in exchange for land just north of community that is covered by lava fields. It is also important to note that building activities and development within protected lagoons or development activities that require the cutting of mangrove species is prohibited by law, even within the boundary of the community.

Although mean density of the "core" community remained almost constant from 2003 to 2007, the extent and density of outlying areas increased with improved road access to parcels as indicated by the increase in median building density and road length between 2003 and 2007 (Table 1). Growth in the number of buildings continued during the period between 2007 and 2009, although building density remained relatively stable.

While the number of years between the dates of the air-photos varies, it is clear that building and road development in the community is a relatively recent phenomenon, and that the rate of growth has increased in recent years as shown by the increased extent and densification of the community. From field observations since 2006, the number of multiple storey buildings also has increased, especially along the beach and in the commercial center of the community. It is common to see buildings with partially completed upper stories, indicating the building's owner anticipates an upward expansion of living space, or rental space in the future as conditions warrant. Future development is also expected in the outlying areas of the lava fields that have yet to be fully developed.

Water and Sewer Infrastructure

The Galápagos Islands lack an abundant source of freshwater (although some freshwater can be found in small crevices and low-flow springs), due to a combination of climate and geology. The Galápagos archipelago's low elevation and surrounding cool waters result in low precipitation and a fairly arid landscape, and the volcanic origins of the islands result in a highly fractured landscape (d'Ozouville *et al.* 2008b) that does not capture and retain precipitation very well. Rainwater that falls in the highlands of the islands generally percolates downhill through fractures in the lava flows, and collects in small underground reservoirs and lagoons at lower elevations along the coast. However, salt water intrusion from the ocean results in reservoirs with a thin freshwater lens that lies above the brackish water (Buckalew *et al.* 1998). This arid environment combined with low precipitation leads to a situation of limited amounts of freshwater available for human use, and, what is available, is often contaminated by salt water due to over-pumping and, increasingly polluted by human waste.

It is from such brackish reservoirs that Puerto Villamil draws its municipal tap water. Tap water for residents and tourists is pumped from two small, connected shallow aquifers, located just north of the community. The water is filtered with large sieves to remove small pebbles and rocks, but is not treated in any other way. The water is pumped through a series of plastic pipes to the community for distribution through a similarly piped network. In the more recently-developed areas of Pedregal 1 and Pedregal 2, water retention tanks collect the piped tap water and then the water is distributed through a pump system that runs on a schedule set by the municipality. Water for the households in the neighborhoods near the dock (Embarcadero) and in the agricultural zone in the highlands (located nearly 30-km from Puerto Villamil) is drawn from two separate shallow aquifers, located in fairly close proximity to the piped water source for the rest of Puerto Villamil. Tank trucks carry the water to households for retention in individual tanks for subsequent use.

In the Galápagos, tap water is provided as a public service for a fee in contrast to drinking water that is only provided by private companies (also for a fee). Variations in the use of tap water in Puerto Villamil, and the associated risk behaviors of the local residents, derived from our interviews, are presented in Table 2. Tap water is primarily used for laundry and bathing, and in some households and restaurants, it is used for washing dishes, food preparation, and cooking. In Puerto Villamil, water quality is characterized by local residents and health care professionals as "poor," although long-term, detailed studies of the water system have not been undertaken. Residents of the community practice a range of use habits to deal with the poor water quality, including adding chlorine to drinking water, using purified water exclusively, and using tap water for everything except for drinking.

Table 2. Tap water use and adaptive behavior (low- and high-risk) with associated health risks for Puerto Villamil, Isabela Island.

Tap-Water Usage	**Lower-Risk Behavior**	**Higher-Risk Behavior**	**Health Risks**
Bathing	Adults only	Adults and children	• Fungal skin infections • Vaginal and urinary tract infections
Washing dishes	Rinse with chlorinated water	No purified rinse	• Gastrointestinal problems
Food preparation	Pre-wash food with chlorine or anti-bacterial agent	No treatment	• Gastrointestinal problems • Parasites
Cooking	Only cook with purified water	Use boiled or untreated tap water	• Gastrointestinal problems • Parasites

Puerto Villamil's drinking water comes from three sources: (1) two local, private desalinization plants, (2) rain water, and (3) bottled water shipped from the mainland. The desalinization plants in Puerto Villamil sell five-gallon plastic bottles of reverse osmosis-filtered tap water to local residents. Some residents have indicated that the processed water is too expensive to consistently use and that the bottles have often been contaminated, owing to the poor methods used to clean and reuse the plastic containers. In the highlands of Isabela, rainwater is collected and funneled into plastic tanks and cement cisterns. This water is consumed by individual residents and their families, and in some cases is sold to residents of Puerto Villamil (as the arid, coastal zone receives much less precipitation). However, collection platforms and tanks are not cleaned regularly and in some poor sanitary practices can contribute to contamination of the drinking water. Water is also packaged in plastic bottles and shipped from the mainland of Ecuador, although the plastic is often of poor quality and permeable, making it susceptible to contamination prior to shipping and upon arrival in the Galápagos.

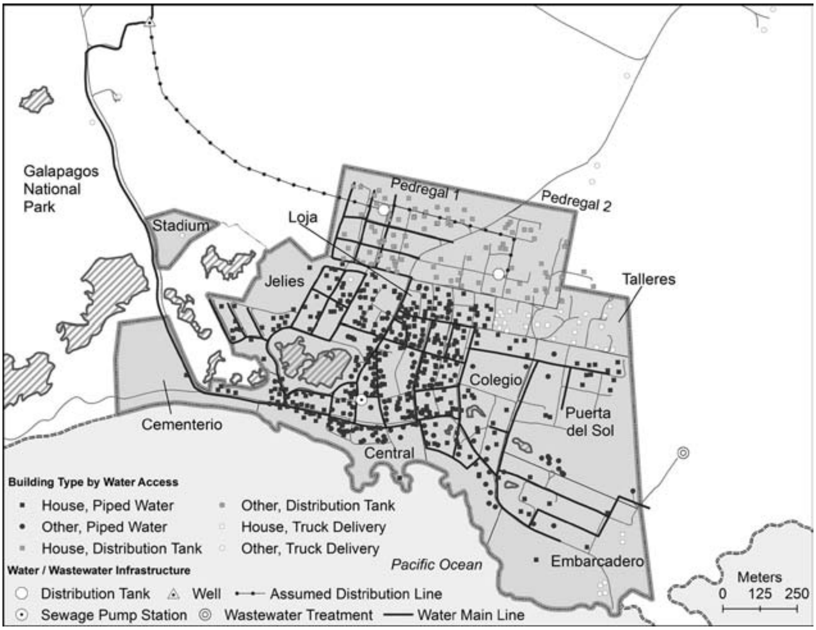

Figure 4. Municipal piped-water system in Puerto Villamil, Isabela Island (~ 2009).

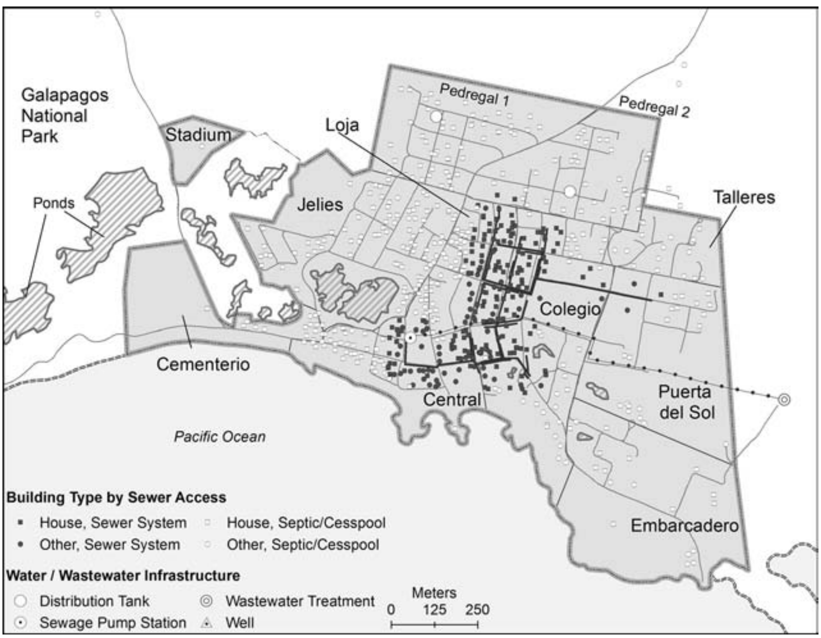

Figure 5. Municipal wastewater (sewer) system in Puerto Villamil, Isabela Island (~ 2009).

Our analysis of the water and sewer infrastructure indicates that while most buildings and structures in Puerto Villamil have access to municipal water, the method of delivery spatially varies (Figure 4), with some buildings connected to the main network (older areas of development), secondary pumping from holding tanks (lava fields), and truck delivery of water to individual household water tanks (most recent development). Approximately 82 percent of the occupied households of Puerto Villamil have access to the municipal piped water network, similar to the 83 percent of households that reported access to the piped water system in the 2006 Special Census of Galápagos (INEC 2007b).

In contrast, the municipal sewer system only provides service to about 40 percent of the households of Puerto Villamil (Figure 5), a figure that is similar to the data on household wastewater disposal reported by the 2006 Special Census of Galápagos (INEC 2007b). Households in the community (and highlands) that are not connected to the sewer system use individual septic tanks, simple latrines, or dispose the effluence in the volcanic cracks and fissures near their dwelling units. The practice of household disposal of waste into the ground is mostly unregulated. The municipality maintains a wastewater treatment system located on the southeastern edge of the community that collects and separates waste from the sewer network, but the wastewater is not consistently treated with chemicals before being dumped into an adjacent fissure in the lava field, and at present the treatment equipment is not working. Near-shore contamination from household dumping, seepage of waste through the fractured geology, and the pumping of water from nearby wells has clear implications for human health, and of increasing concern for the ecological health and vitality of sites visited by the local community as well as international tourists and visitors from throughout the archipelago.

Not only is water quality a concern for people and the environment, but so too is the concern for water quantity. The arid and semi-arid regions of the island have low and inconsistent precipitation patterns, and almost no fresh surface water. The movement of water from the humid highlands to the populated coastal zone occurs through the vertical and horizontal infiltration through the porous volcanic geology and down-slope towards the coastal community. With over-pumping from the community wells to increase the capacity for residents and tourists, salt-water intrusion into the aquifer can occur, particularly with increased pumping. Saline water is often detected in the water pumped at the community wells. In nearly all situations in the Galápagos, including Isabela island, population growth and development have outstripped the existing water, sewer, and sanitation infrastructure.

Water and Human Health

Up to 70 percent of local illnesses in Puerto Villamil may be caused by the consumption of, or exposure to, contaminated water, according to our 2009 interview with a community physician. Common water-related illnesses include gastrointestinal problems such as diarrhea and gastritis, fugal skin infections such as ringworm, intestinal parasites, and vaginal or urinary tract infections. Young children (1-4 years of age) are most affected by the effects of tap water and the related health issues, because their immune systems are under-developed, they practice poor hygiene, and tend to experience higher exposures to contaminated sources of water. School-aged children undergo parasite testing three times a year, and they cannot enroll in school if they test positive. National government-subsidized healthcare offices and clinics exist on each island. Together with private or community sponsored clinics, as is the case in Puerto Villamil, they provide care to residents and tourists. Staffing levels, facilities, supplies, and quality care are commonly in short supply, but less so on the islands with larger populations and improved health care networks, i.e. Santa Cruz and San Cristobal Islands.

Most residents of Isabela self-medicate with over-the-counter anti-diarrheal and anti-fungal medications. When problems are severe, residents seek care at the public or private clinics, but many residents prefer to go to Santa Cruz Island or to the Ecuadorian mainland for higher quality care. Of those who seek health care in Puerto Villamil, nearly 70 percent go to the public health sub-center, 20-percent go to the municipal clinic, and 10 percent see private doctors, when available.

Local doctors and health clinics advocate good hygiene and household use of available water sources to prevent and treat water-related illnesses, but residents believe that the government has the responsibility to provide residents with a reliable source of potable tap water. Private attempts to finance or engineer potable drinking water programs within the archipelago (Spanish Cooperation Agency and the Deutsche Bank) have failed (Matthias Espinosa, personal communication, January 24, 2010).

While the public's concern for water quality has been a long-standing issue, the first assessments of water quality in Puerto Villamil only occurred in 2007 and 2008. In conjunction with the Japanese International Cooperation Agency (JICA), the Galápagos National Park conducted a preliminary analysis of water quality for various sites on Isabela (López Medina *et al.* 2007, 2008). Water samples were drawn from the primary municipal well (El Chapin), the secondary well (El Manzanillo) that is connected (underground) to the primary well, a nearby lagoon (Poza Las Salinas), homes in the community of Puerto Villamil (tap water), at the INGALA Building, and at the municipal dock. The results of the study indicate that for both years potential hydrogen, dissolved oxygen, nitrates, and turbidity levels were within "permissible limits" (López Medina *et al.* 2007, 2008). However, fecal coliform was detected in tap water samples taken from local homes, as well as at the El Manzanillo well, where the provincial council draws water for use in the highlands (Figure 6). Fecal coliform levels were highly variable throughout both years for the two sites, although there was a general trend of increasing concentrations of fecal coliform in local homes beginning at the end of the dry season in October 2007 and continuing into 2008. On average, the fecal coliform levels detected in local homes exceeded the permissible limit of 600nmp/100 mL.

The results of the water sampling study show that from 2007 to 2008, the salinity levels of water from the El Manzanillo well and local homes increased steadily, and exceeded the freshwater limit of 1000 mg/L (Figure 7). The increase in salinity over times is likely the result of over-extraction of water from the two community wells (El Chapin and El Manazillo), which leads to brackish water being drained from the deeper parts of the shallow aquifer, resulting in water that is too brackish for human consumption.

Water and the Environment

From an environmental health perspective, the coastal lagoons of Isabela, particularly those that border Puerto Villamil, are important sites for migratory and local bird communities, as well as aquatic fauna (Gelin and Gravez 2002). Negative relationships have been reported between salinity levels and fish diversity in tropical coastal lagoons (Sosa- López *et al.* 2007).

The geographic pattern of Puerto Villamil, a Ramsar site --wetlands of international importance designated under the Ramsar convention-- are shown in Figure 8, as well as the community of Puerto Villamil and the town's urban structures. Figure 8 also shows the density of dwelling units and commercial buildings that are in close proximity to the Las Salinas lagoon. Many of these buildings do not have access to the existing sewer system and, therefore, water is contaminated through dumping, runoff, and solid waste.

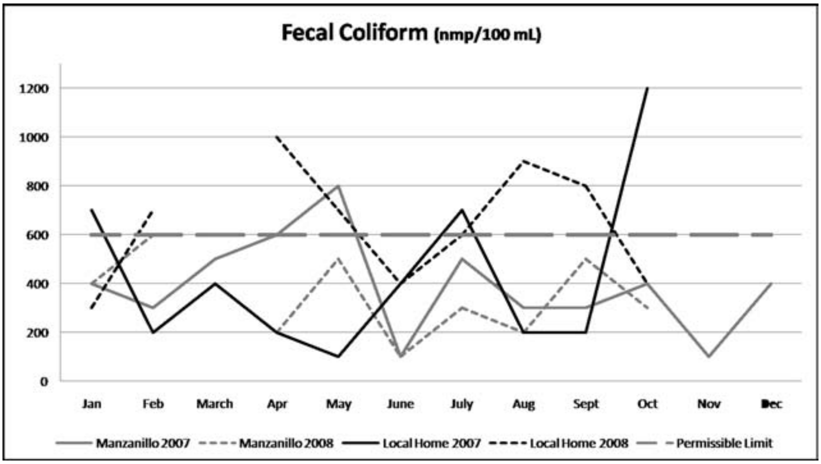

Figure 6. Fecal coliform levels are shown for water samples drawn from the El Manzanillo municipal well, that delivers water to the highlands via truck and for samples taken from tap water found in local homes in Puerto Villamil, Isabela Island for 2007 and 2008. (Source: López Medina *et al.* 2007, 2008).

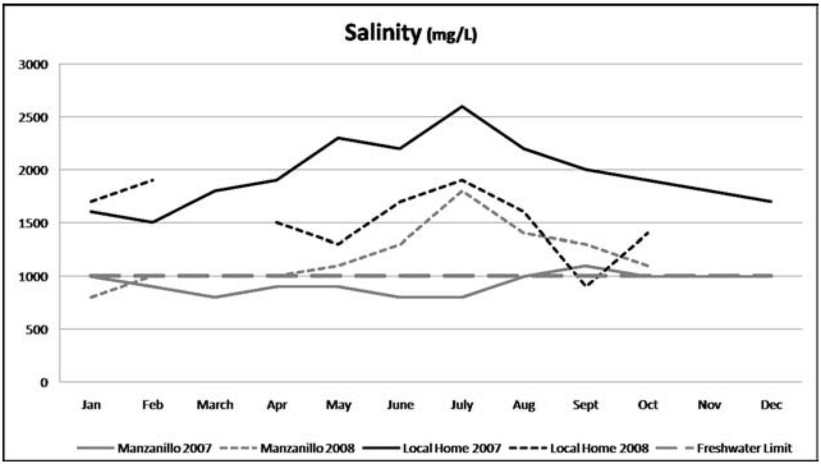

Figure 7. Salinity levels are shown for water samples drawn from the El Manzanillo municipal well, which delivers water to the highlands via truck, and for samples taken from tap water found in local homes in Puerto Villamil, Isabela Island for 2007 and 2008. (Source: López Medina *et al.* 2007, 2008).

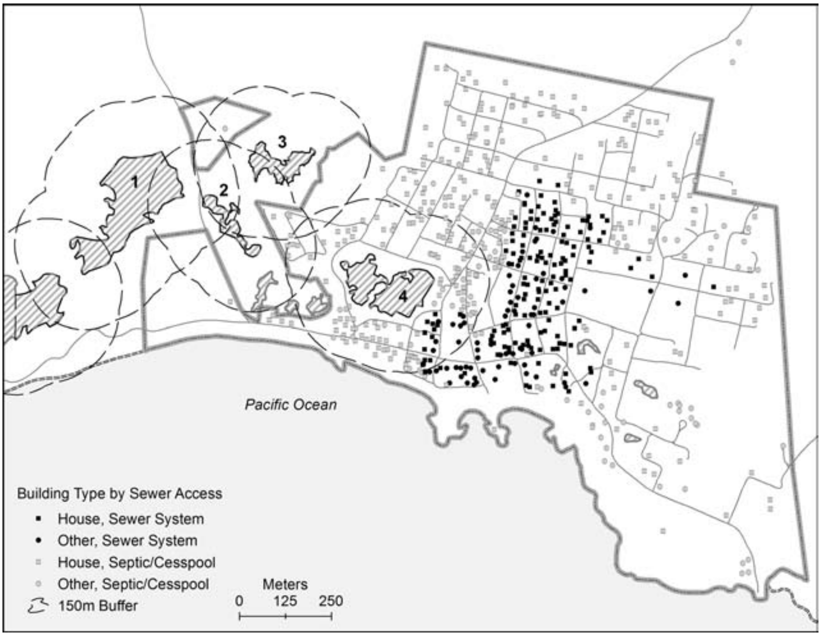

Figure 8. The study area of Puerto Villamil, Isabela Island and the adjacent Galápagos National Park.

Sensitive coastal forest species, particularly mangroves, also are located in close proximity to Puerto Villamil, as well as to the coast road that links the community to the nearby beaches and tourist attractions. Mangroves that occur in such arid settings, typical of the Puerto Villamil area, are generally nutrient-limited, and therefore, increases of nutrients from sewage may actually increase mangrove productivity, at least in the short-term (Alongi *et al.* 2005). As only one peer-reviewed study of mangrove forest in the Galapagos has been conducted (Howmille and Weiner 1968), little is known about the productivity and general behavior of mangroves relative to species type, terrain and habitat settings, and critical thresholds of nutrient flux and salinity in the Puerto Villamil region. Studies from other areas with the same species such as McKee (1995) indicate that seedling establishment and survival of mangroves are affected by physio-chemical stress suggesting that changes in environmental conditions can alter the form and composition of mangrove forests. Furthermore, the impacts of human alterations can continue well beyond the period of disturbance as the feedbacks between vegetation and geomorphic processes continue to define new sites of ecological stability (Dahdouh-Guebas *et al.* 2004).

In addition, 80 percent of the Galápagos flamingo population inhabits the lagoons on Isabela island that are adjacent to the community (Gelin and Gravez 2002). These are the same sites that have been directly and indirectly impacted by human activities that alter the quantity and quality of the water that feeds these systems. In addition to water contamination, the Las Salinas lagoon is further plagued by the cutting of mangroves for urban expansion. Las Diablas, a lagoon located in the protected area of the Galápagos National Park, is threatened by changes in water salinity levels possibly caused by fresh water extraction and development along the coastal road that has separated the lagoon from regular ocean-flushing during high tide. Furthermore, the presence of Kikuyo grass (*Pennisetum clandestinum*), introduced by residents in the 1950s, present another challenge (Gelin and Gravez 2002). The grass is colonizing the edges of the lagoon, replacing open water with a dense mat-like marsh. A major tourist destination, Las Tintoreras, is also in close proximity to the community. The site contains a number of iconic species such as the Galápagos penguin that is critically important to local tourism. However, the impact of the decreased fresh water supply and declining water quality on the nearby inter-tidal and marine ecosystems is not yet known due to a lack of short and long-term monitoring.

Conclusions

This study draws attention to the connections between urban growth, water and sewer infrastructure, and human and environmental health in Puerto Villamil on Isabela Island. The study also has implications for the broader archipelago, because of similar human use patterns, precipitation constraints, environment conditions, and the generally deficient urban infrastructure. Since the UNESCO "At Risk" declaration in 2007 and the Ecuadorian government's call to action that preceded it, the rhetoric surrounding social and environmental issues has increasingly been linked in policy debates and land use practices. While very little has actually been done to encourage responsible urban development, the need to embrace the causes and consequences of human-environment interactions has been raised to a new level of concern and discourse. There remains, however, a lack of public representation and social activism beyond the level of individual communities, making long-term projects difficult to initiate and impossible to maintain. For example, although recent efforts have been made to develop a regional water and wastewater plan that involves local stakeholders (Gildemyn 2007), these efforts and discussions have resulted in little action.

From an environmental health perspective, the coastal lagoons of Isabela, any of which are protected as a Ramsar Wetlands Site, particularly those that border Puerto Villamil, are important sites for migratory and local bird communities, as well as aquatic fauna. These sites have been directly and indirectly impacted by human activities that alter the quantity and quality of the water that feeds these systems. For instance, La Salina, a lagoon located within the community of Puerto Villamil, is contaminated by waste-water from adjacent homes, solid waste, and cutting of mangroves for urban expansion. Las Diablas, a lagoon located in the protected area of the Galápagos National Park, is threatened by the presence of Kikuyo grass, introduced by residents in the 1950s. The grass takes-up a significant amount of water from the soil, and threatens the existence of wetlands where it grows.

From a methods perspective, this study integrates remote sensing image analysis of aerial photography and satellite imagery; GPS coordinates of building location and the geographic position of the water, sewer, and sanitation infrastructure of Puerto Villamil; as well as qualitative interviews with 15 individuals including six community health care professionals, parents of six local households, four community engineers, and 1 provincial health care administrator. The intent of the mixed methods approach is to conduct a space-time analysis that relies upon the spatial precision of GPS technology, the multi-temporal perspective of historical to contemporary aerial photography and satellite images, and interviews with key informants as context to the formulation of a narrative that links population, health, and environment in the Galápagos.

In short, the expanded human imprint in the Galápagos is having deleterious consequences on the environment of the "Enchanted Islands." Increased population density in spatially restricted communities, urban infilling of structures, dramatic expansion of the tourism industry, fractured volcanic landscape, and the deficient water, sewer, and sanitation systems in the Galápagos have severe implications for human and ecological health. Limited data collection campaigns and the paucity of spatially-explicit information make quantification of human-environment interactions difficult, but anecdotal evidence from health practitioners, residents, tourists, and preliminary data suggest an environment that is under stress from an expanded human imprint that is exacerbated by the peculiarity of its geographic site and situation.

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