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Freshwater lens assessment of karst island water resources: towards an interdisciplinary protocol

Robert DiFilippo, Lee Bosher and Carlos Primo David

Abstract: *Fresh groundwater lenses on karstic oceanic islands form a vital resource sustaining local populations. However, this resource is susceptible to saltwater intrusion through human drivers (over-abstraction) and natural processes (variable precipitation and storm surges). There is a paucity of means to assess the risks that freshwater lenses are exposed to. This is partly driven by a poor understanding of the root causes of saltwater intrusion, which leads to potentially inappropriate freshwater management strategies. Thus, effective management of these freshwater lenses requires a baseline understanding of the processes that drive saltwater intrusion and the degradation of freshwater lenses, and the temporal and spatial variability of these processes. Dynamics of such freshwater lenses involve an interplay between physical, chemical, and socio-economic processes; therefore, finding a solution necessitates an interdisciplinary approach and a range of data collection strategies. This approach was formalized in a Freshwater Lens Assessment Protocol (FLAP). Results from the research developed and tested on Bantayan Island in the Philippines reveals a sufficient freshwater lens to support the current and projected population; however, local officials are operating abstraction wells from the wrong locations on the island. Such locations are utilized due to ease of access to existing infrastructure and government boundaries, but do not consider technical factors that influence saltwater intrusion. FLAP is an appropriate, cost-effective, interdisciplinary tool that uses a pragmatic approach to data collection, interpretation, and integration into an observational model. Continuous adjustments are possible through ongoing monitoring of the model, offering opportunities to evaluate the efficacy of resource management strategies.*

Keywords: climate change, karst, freshwater lens, saltwater intrusion, freshwater resource assessment

Understanding the influence of global climate change on the hydrologic cycle in small oceanic islands has become an important field of concern and research (Ogurcak and Price, 2018). Freshwater is a critical natural resource for oceanic

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island ecosystems and communities. Its importance is recognized by the UN, which identifies water security as an important underpinning of the Sustainable Development Goals (SDGs) (Gain et al., 2016; UNESCO I-WSSM, 2019). However, according to recent estimates of island communities, approximately 65 million people live on oceanic islands, with fresh groundwater as their only source of fresh water (Thomas et al., 2020). Mapping by Hong et al. (2017) suggests that approximately 20–25 per cent of the global population depends largely or entirely on groundwater obtained from karst aquifers (a water-bearing zone that flows through a special landscape formed by the dissolution of soluble rocks including limestone and dolomite). Islands composed of carbonate rocks present complex anisotropic (anisotropy in an aquifer can be defined as the difference in hydraulic conductivity in two different directions) environments that produce distinct karst geology, atypical of isotropic aquifers (i.e. hydraulic conductivity is equal for groundwater flow in all directions) present in other coastal environments.

Karst aquifers are characterized by solution-enlarged discontinuities (i.e., joints, bedding planes, and faults) and form complex interconnected drainage networks (Xanke et al., 2015). The karst aquifer under investigation is vulnerable to saltwater intrusion through natural and anthropogenic stressors. The fundamental complexity of the aquifer, as stated by White (1999) is that 'a karst aquifer is a triple porosity medium, consisting of the rock matrix (intergranular porosity), the fractures and bedding planes and the karstic conduits' (cited in Gondwe et al., 2011: 25). In oceanic island environments, these complexities are exacerbated as interactions with saltwater affect the morphology and dynamics of freshwater lenses. These conditions pose great challenges for local stakeholders in their attempts to sustainably exploit the freshwater lenses.

The Joint Monitoring Programme (JMP) of the WHO and UNICEF have responded to this by taking the initiative to accelerate progress towards universal, sustainable access to safe drinking water and sanitation through a system of global monitoring and reporting (Manka, 2013). This approach demanded strong political commitment in response to increasing public awareness of poor water sector performance. Progressive implementation following well-defined priorities and use of a comprehensive, holistic approach was central to this.

To achieve suitable change on the ground, improved knowledge and understanding of the requirements, performance, and resource management of the water sector is vital. This demands a comprehensive, interdisciplinary approach (Stewart and Gill, 2017) and an understanding of issues such as access to clean water. It is important also to address complex human-environmental interactions and to ensure the engagement of geoscientists, hydrologists, social scientists, economists, and others (e.g. Petcovic et al., 2009).

The availability of baseline data on water resources is crucial to define the problem as is establishing monitoring networks and engaging local stakeholders highlighted by the UN in the 2030 Agenda for Sustainable Development (A/RES/70/1; United Nations, 2015). This is particularly pertinent for small, karst oceanic islands where monitoring data provides important insights into freshwater lens performance and utilization. Although national political commitment towards effective water resource management is recognized in the Philippines, local capacity to proactively address this is often absent (Department of Science and Technology, personal communication, 2017) or compromised by a lack of understanding of the dynamics of the freshwater lens and its utilization (Vandenbohede and Lebbe, 2002; Bailey et al., 2012; Igel et al., 2013; Röper et al., 2013; Holding and Allen, 2015; Stoeckl et al., 2016).

This paper introduces an interdisciplinary approach that can be used for the systematic characterization of a freshwater lens beneath a karstic island. It is particularly relevant for low- to middle-income countries (LMIC). The Freshwater Lens Assessment Protocol (FLAP) is a workflow approach to the collection of both technical and social data sets, which, when combined, can inform local stakeholders on the status of saltwater intrusion, how water resources are managed, and the opinions of national, provincial, and local stakeholders on water resource policy enforcement issues and their capacity for managing a freshwater lens.

Literature review

Existing freshwater lens research

Werner et al. (2017) report on more than 50 years of research that has resulted in significant progress in hydrogeology observations on atolls (islands formed of coral, generally with a ring-shaped reef). However, freshwater lens research has largely been performed in locations where groundwater monitoring networks were established; therefore, a dearth of data still exists on all but a few atoll islands.

Karst hydrogeology research has largely focused on coastal and island karstic landforms in the Mediterranean Sea and Atlantic Ocean (e.g. Jones and Banner, 2003; Tulipano, 2003; Polemio, 2009; Fidelibus, 2019). The Carbonate Island Karst Model (Mylroie et al., 2001) identifies a set of processes and conditions that are unique to karst islands, including: 1) enhanced dissolution at the surface, base, and margin of the freshwater lens; 2) the history of vertical migration and positioning of these margins based on glacio-eustatic (i.e. global sea-level changes resulting from terrestrial ice-volume changes) and tectonic-driven changes in relative sea levels; 3) the size of the island's catchment area in relation to the perimeter (that may vary with change in sea level); 4) the hydrological implications of the eogenetic (i.e. below the zone of the influence of surface processes) environment of the limestone; and 5) the location of the island's carbonate basement contact associated with sea level and the island surface over time.

Establishing a local groundwater monitoring network and collection of physical parameters is essential to collect the relevant baseline parameters that inform the dynamics of freshwater lenses and the potential for saltwater intrusion on karst islands. This underpins the establishment of a conceptual ground/hydrology model that can then be refined as further monitoring information becomes available from local stakeholders. It is important to recognize that for data to be meaningful, the heterogeneous nature of the karstic aquifers requires 1) regional networks with a higher density than for non-karstic aquifers; 2) greater monitoring frequencies; and 3) extended monitoring periods (e.g. Polemio et al., 2009; Fidelibus, 2019; see also COST Action 620 (Zwahlen, 2018)).

Social dimensions of freshwater lens research

The global importance of saltwater intrusion is well established in the literature (Custodio and Bruggeman, 1987; Wu et al., 1993; Bocanegra et al., 2010; Werner et al., 2012; Badaruddin et al., 2017). Progressive degradation of coastal freshwater resources due to saltwater intrusion reduces the potential for their sustainable use and exploitation. In the Philippines, population growth and increasing poverty in coastal communities, combined with weak regulatory enforcement, exacerbate these problems (Sales, 2009). The physical characteristics of the coastal zone are, therefore, inextricably linked to the socio-economic and cultural dimensions (Sales, 2009). This is also supported by O'Keeffe et al. (2016) who emphasize the need to integrate knowledge of user behaviour (including their attributes and drivers) with what is known about the physical nature of the resource to develop realistic and sustainable water security management practices.

Bocanegra et al. (2010) conducted a comparative analysis of 15 coastal aquifers in South America, looking at how the state of knowledge contributes to their management. This varied from virtually no information (most commonly observed) to 'complete' conceptual aquifer and management models. In all cases where groundwater exploitation was common, there was generally little evidence observed to support resource planning and management, insufficient monitoring networks, and a need to raise awareness of the state of the groundwater resource to achieve appropriate planning and management programmes.

It is accepted that saltwater intrusion is a global problem for coastal water resources, worsened by sea level rise, climate change, and a growing dependency on groundwater resources for water supply (Werner et al., 2012). Small island communities are particularly at risk; however, there is a scarcity of information on the quantity and quality of groundwater resources on karst islands in countries such as the Philippines. The current and future demands from private and commercial abstraction are unknown due to lack of monitoring and planning at the local level. For sustainable management, these demands need to be offset against other stressors such as changing precipitation patterns driven by global climate change, rising sea levels, and consequent changes in freshwater recharge regimes. Uncertainties caused by these stressors generate significant further difficulties for the management of natural freshwater resources (Pahl-Wostl, 2007).

To better understand the opportunities to access freshwater lenses sustainably and reliably on karst islands (in terms of both quantity and quality), it is essential to characterize the dynamic nature of these lenses. There is a risk that well extraction of freshwater can reach a critical threshold beyond which irreversible damage to the supply will be manifested. Knowing more about the long-term performance of freshwater lenses will, therefore, assist legislators to develop appropriate regulatory frameworks and will give well operators the information to effectively plan and adjust their abstraction practices. However, the problems are significant due to the complexity of the karst aquifers, insufficient monitoring, a lack of financial support, and limited enthusiasm to implement regulatory frameworks. Thus, the effectiveness of small island countries to manage their water resources is mostly constrained by limitations of their capacity to construct the baseline (Ward et al., 2016).

Local level stakeholders lack adequate funding, experienced staff, and often the proper hardware to effectively manage their water resources. As the data sets necessary for effective management are typically not available to them, there is often a reliance on poorly constrained indicators that, without a formal logical framework only deliver very basic insights.

There is broad recognition of the integration of social perspectives and physical processes, but relatively few studies have actually approached the problem in this way. The research objective was to establish a formal approach to integrate quantitative and qualitative data covering a range of topics and to improve understanding of water resources in this complex milieu and provide a roadmap for stakeholders. Similar to Bocanegra et al. (2010), this study evaluates the regulatory framework of the three tiers of government and assesses the activities of well owners, coupling this with the physical data (e.g. Werner et al., 2017) to achieve a systematic characterization of the freshwater lens on Bantayan to enable the development of sustainable freshwater lens management practices.

The research area

The Philippines Archipelago is composed of more than 7,100 islands and islets stretching about 1,854 km from north to south. Briones (2005) describes the archipelago as having a total coastline of about 18,000 km, an area that covers about 11,000 km^2 of land and about 70 per cent of the 1,526 municipalities, including large cities located within the land portion of the coastal zone. Moreover, about two-thirds of the country's population live in the coastal zone and are, therefore, directly influenced by the coastal environment (Briones, 2005).

Site selection

Within the Archipelago lies the province of Cebu, which is central to the Archipelago. The island of Bantayan is located approximately 15 km north-west of Cebu, in the Visayan Basin (Figure 1). The island covers some 113 km^2 and reaches a maximum elevation of 82 m above sea level.

Bantayan Island is located off the north-west coast of Cebu and is strategically a fishing island with a land area of 8,163 hectares (Philippine Statistics Authority, 2013). According to the Philippines Statistics Authority (2015), Bantayan has a population of 144,000 distributed across three municipalities.

Geologically, the island is composed of a calcarenite, described by Folk et al. (1973) as a classic limestone consisting of sand grade calcite or aragonite particles that have undergone karstification. Reef formation was followed by an extended period of intermittent exposure resulting from the interaction of glacioeustasy and tectonoeustasy (i.e. global change of sea level resulting from change in capacity of the ocean basins from plate tectonic movement) (Jahn and Asio, 2006). Now emerged from the sea due to regional tectonic activity, the land surface has been karstified.

This geology is complex and the predominant research areas for such a geologic milieu are in the Caribbean and Mediterranean Seas and the South Pacific. Therefore,

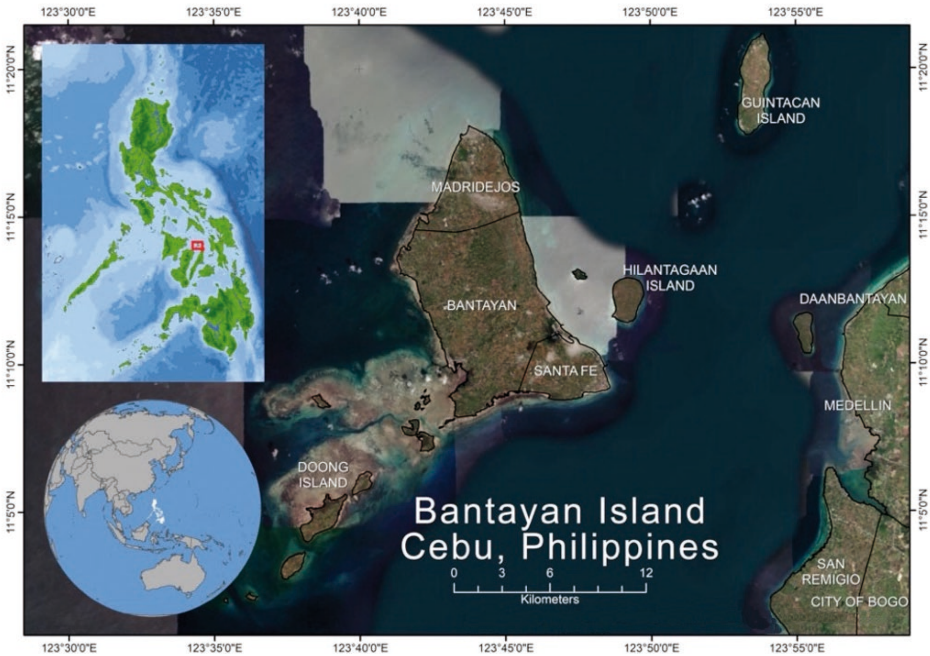

Figure 1 Satellite image: Philippines, Archipelago and Bantayan Island
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

the opportunity to bring this research programme to a region of the world lacking research of this type created a unique opportunity.

Other factors for consideration by this study were:

- the towns' primary dependence on groundwater for water resources;
- the trans-boundary challenges between the three local government units (LGUs) and one freshwater lens;
- a growing population which was reported by the United Nations Population Fund (UNFPA) as an increase of 1.4 per cent annually from 2015 to 2020 (UNFPA, 2021), resulting in a greater demand for groundwater; and
- expanding commercial demands for groundwater from poultry and tourism industries.

Methodology

FLAP is a workflow approach designed to characterize a freshwater lens through collection and evaluation of technical and social data sets. A critical review of the literature identified the necessary data sets for developing an island-wide observational model that incorporates the data from the research; this will inform local stakeholders about the status of the freshwater lens relative to saltwater intrusion over a 12-month research period. The observational model was developed after the

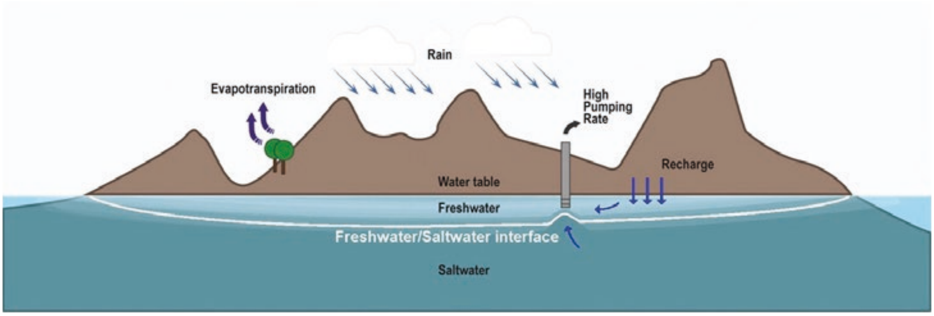

Figure 2 Conceptual model of a typical island landform (Alberti et al., 2017)

work of Bredehoeft (2005), where the model was intended to simulate a real and naturally occurring system or process. The goal of this model is to support local water resource management decision-making.

Figure 2 presents a typical conceptual model. This illustration highlights the key data needed to develop an island-wide observational model. Therefore, from this simple conceptual model, the research observational model was developed. The key data attributes collected as part of this research include precipitation, estimates of evapotranspiration (i.e. the process by which water is transferred from the land to the atmosphere through evaporation from the soil and other surfaces and by transpiration from plants), hydraulic head measurements, computations of freshwater lens thickness, and tidal forcing (i.e. the moon's gravitational pull that generates ocean tidal forces). In addition, digital elevation model data and well location references were also assimilated into the observational model to provide a complete representation of the observational data sets culminating from this research. This merging of technical data sets is shown to transform the conceptual model example (Figure 2) into an observational model of the research area as presented later in this paper.

The study did not intend to produce a three-dimensional groundwater model of the dynamic processes associated with saltwater intrusion into a freshwater lens. Instead, the aim was to design a cost-effective, technically rigorous, non-invasive methodology for the development of an island-wide observational model, at the same time, advancing scientific knowledge to strengthen the technical capacity of stakeholders. Finally, engagement with national, provincial, and local government was critical to ensure the research findings could be implemented through adaptive water resource management (AWRM) concepts, which applies a structured, iterative process of decision-making amid uncertainty.

As previously stated, both quantitative and qualitative research were used. Technical data sets identifying geology, hydrogeology, and geomorphologic land features and associated recharge areas were integrated with light detection and ranging (LiDAR), hydrochemical, and well hydraulic head data sets. Social data sets, including well owner questionnaires and semi-structured interviews, were examined to determine themes relating to governance, water resource management policy enforcement, technical capacity in government, and local water access and availability issues. These quantitative and qualitative data sets are presented in Table 1.

Table 1 Quantitative and qualitative data sets

Data type and relative time frame for completion	*Number*
Social	
Well owner questionnaires issued (2 months)	37
Laboratory reports issued (twice during the 12-month research period)	74
Semi-structured interviews conducted (6 months)	30
Technical	
Geomorphologic features mapped (9 months)	41
Well field assessment (2 months)	53
Pumping wells assessed (3 months)	25
Groundwater samples analysed (4 months)	206
Analyses processed in the laboratory (2 months)	1,442
Analyses processed in the field (4 months)	1,030
Tidal studies conducted (1 month)	4

Described below are the specific quantitative and qualitative data sets and sampling approaches that were incorporated into the research methods used.

- Groundwater chemical data identifying specific salts were examined in both the field and laboratory for the characterization of saltwater intrusion into the freshwater lens.
- Geologic and geomorphologic information gathered was geocoded to actual field locations for determination of these factors relative to the groundwater chemistry data.
- Hydraulic head measurements were recorded for selected wells to determine the regional groundwater flow direction and other research-specific hydrogeologic behaviour of the freshwater lens.
- Groundwater flow and operational data were collected from LGU and private well operators.
- Groundwater temperature data collected during groundwater sampling events were examined to determine groundwater flow characteristics of the freshwater lens (FWL) along discrete transects beginning in the recharge area and culminating at the coastal boundary (i.e. zone of discharge).
- To address the inland extent of tidal forcing and the influence of the local tidal force upon the freshwater lens, a series of tidal studies were performed. Examining local tidal data, a series of time versus groundwater elevation charts were developed. Tidal efficiency and tidal lag analysis were conducted and in addition, hydrochemical variance over the tidal cycle was examined.
- Questionnaire data were collected from well owners participating in the groundwater quality research.
- Semi-structured interviews were completed with key respondents at local, provincial, and national levels who actively work in the water resource field.

Technical data sets, including remote sensing imagery, climate monitoring, well inventory data, and field geologic and hydrogeologic data collected and evaluated formed the content of geologic mapping and was necessary for interpretations of groundwater elevation and groundwater gradient map creation. These observations were critical in understanding the morphology of the FWL. Water quality data sets were then incorporated into the geologic mapping to create salt plume analysis and delineation.

Social data sets, including well owner questionnaires and semi-structured interviews, assess the availability of groundwater and the quality of available water over a calendar year. Assessing the variance in water availability due to seasonal variations in precipitation aided in the interpretation of FWL morphology and salt plume configurations.

The technical data creates a physical model of the environment, while the inclusion of socio-economic data incorporates stakeholder sentiment and actual well operational data sets in freshwater lens utilization. This interface between data sets introduces many issues in water resource management that include transboundary issues for government in safe well placement, protecting recharge zones from development, and the temporal variability in water quality and freshwater lens capacity driven by changes in recharge and its influence on freshwater lens morphology. This interface highlights that for effective water resource management it is imperative to operate in both technical and socio-economic dimensions. Combining the two data sets, the island-wide observational model was developed to present a clear and concise picture of the FWL beneath the study area and inform stakeholders of this natural dynamic system. This holistic methodology and non-invasive tool provides a systematic technical assessment of the freshwater lens, while incorporating an additional social dimension to the research (Figure 3). The convergence of geologic, hydrogeologic, and hydrochemical data sets with survey instrument dissemination and semi-structured interviews are presented below.

Results and discussion

The pressures imposed on karst islands resulting from natural and anthropogenic forces are summarized in Table 2. The stressors listed are those identified in the literature and serve as criteria for the architecture of the FLAP. The potential of the FLAP to yield viable output for improved management of groundwater resources was assessed during this research.

The anthropogenic and natural stressors, and the associated challenges, were incorporated into the interpretations of the data sets. Principally, there are challenges that can be augmented by behaviour changes, such as improved water management and informed land development practices. However, the data is needed to inform stakeholders and establish risk of water quality degradation from saltwater intrusion. The assimilation of data sets is fused into two unique illustrations and serves as the island-wide observational model for the research area (Figures 4 and 5).

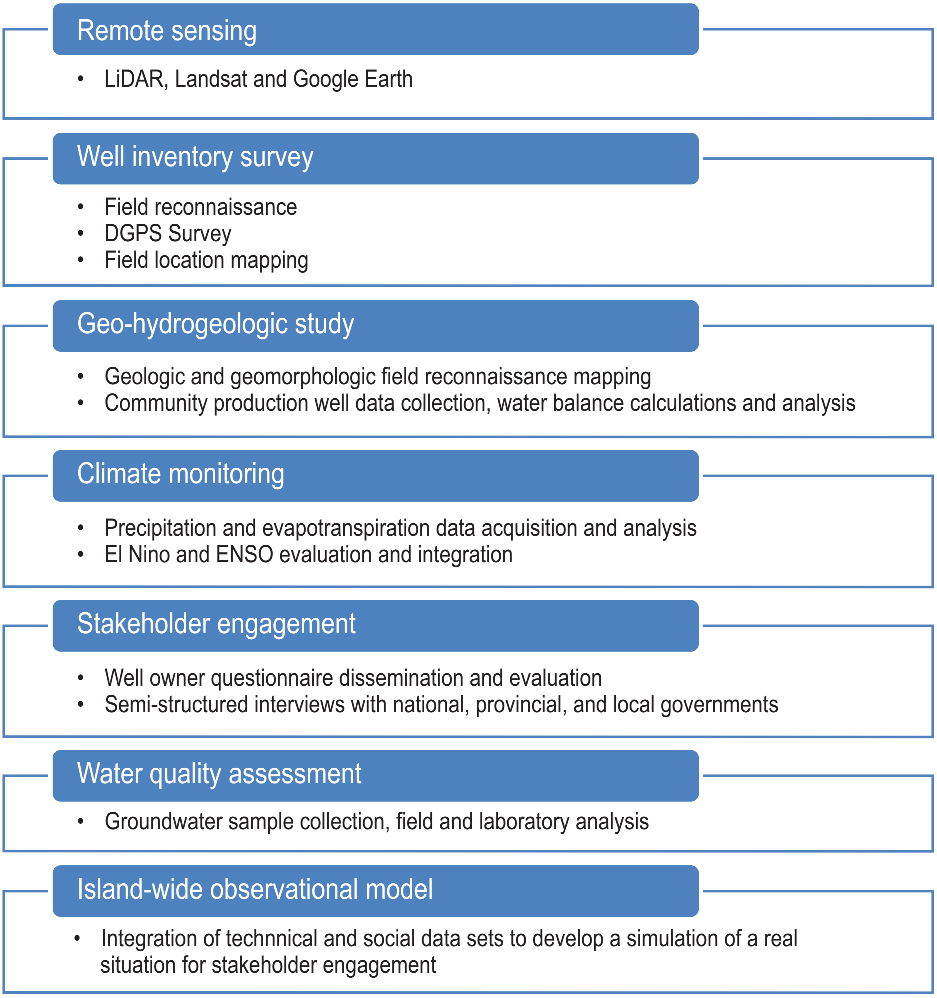

Figure 3 Quantitative and qualitative data summary (Author)
Note: DGPS: differential global position system, ENSO: El Niño Southern Oscillation

Table 2 Challenges on karst islands

Type	*Stressor/Result*
Anthropogenic	Over-abstraction/Saltwater intrusion
	Rising population/Increase demand
	Economic expansion/Increase demand
	Land development/Reduction in recharge
Natural	La Niña and El Niño/Recharge reduction
	Sea level rise/Saltwater intrusion
	Increase storm frequency/Recharge reduction

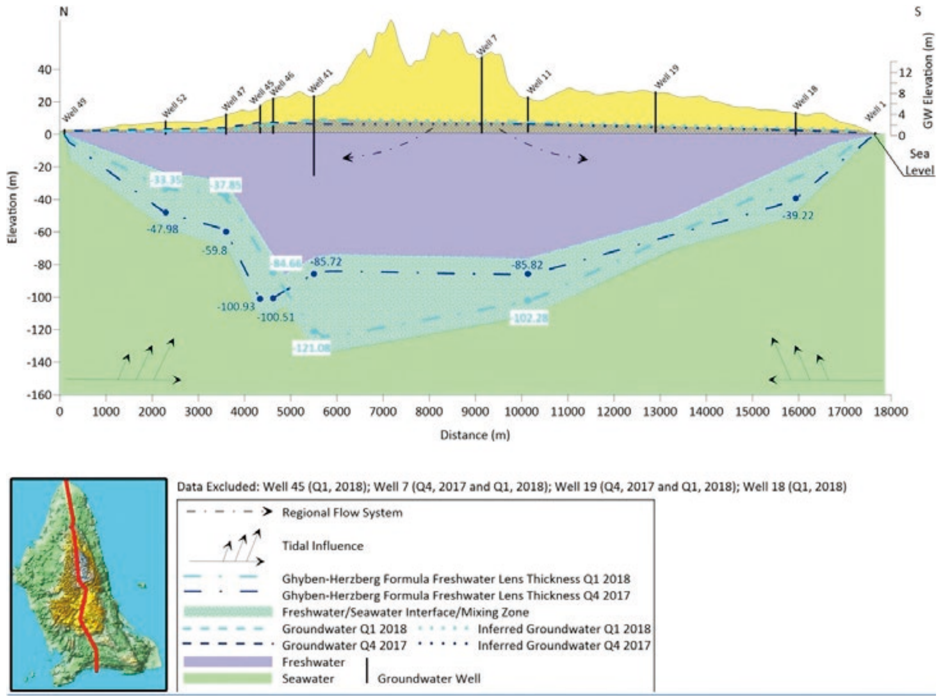

Figure 4 Island-wide observational model north–south perspective, Bantayan Island, Cebu Province, Philippines

Two unique perspectives are presented: the north–south perspective is a longitudinal view along the primary axis of the freshwater lens (Figure 4); the west–east perspective is a cross-sectional view of the freshwater lens perpendicular to the primary axis (Figure 5).

The model illustrates a hydrogeologic system with inputs (precipitation), outputs (evapotranspiration and abstraction), the geology examined, and its influence on freshwater lens morphology, the effects of tidal forcing on the freshwater lens dynamics, the hydraulic head data from the well field, abstraction data sets and computed hydrogeologic variables, and the freshwater-saltwater mixing zone derived from the Ghyben-Herzberg formula. Groundwater discharge at the coastal boundary has not been accounted for in this model since it was beyond the scope of the research. The model presents a longitudinal and transverse view of the freshwater lens under two climatic extremes, the rainy season and the dry season.

Described below are the critical observations from the island-wide observational model north–south perspective (Figure 4):

- Tidal forcing is evidenced along both north and south shorelines, with resulting mixing zones exhibiting areas of passive saltwater intrusion.
- Hydraulic head data and associated freshwater lens morphology are similar to topography where the maximum amplitude of the hydraulic

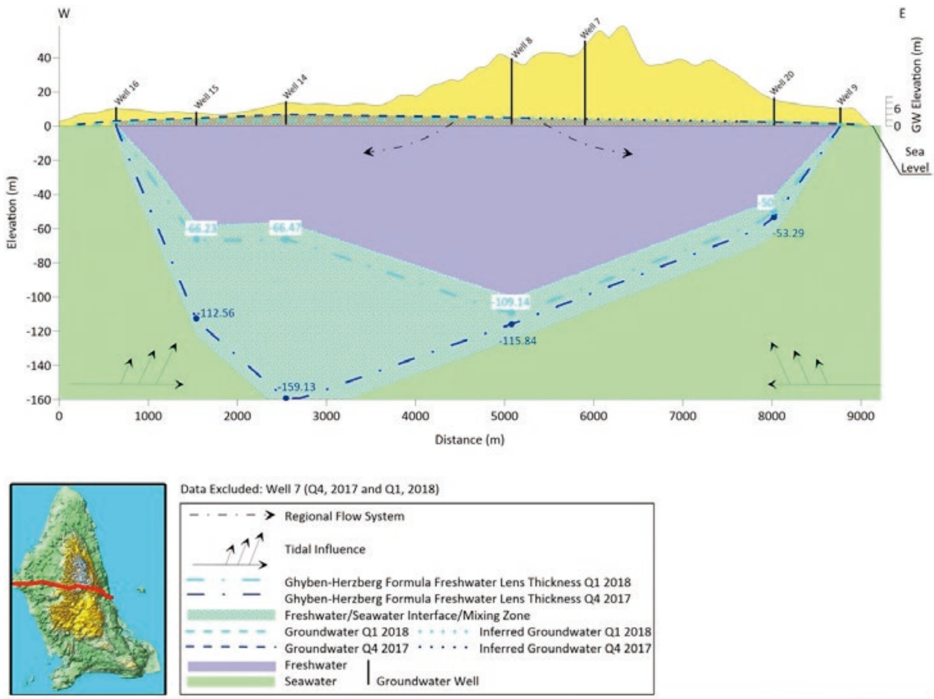

Figure 5 Observational model west–east perspective, Bantayan Island, Cebu Province, Philippines

head is in a recharge area, central to the island and is affected by seasonal recharge dynamics, whereby the rainy season displays the more robust freshwater lens.

- Freshwater-saltwater mixing zone seasonal symmetry is evident throughout the two-dimensional profile, except in the area between wells 41 and 11, where an inversion of the mixing zone is noted in the area of the Madridejos Community Water System (MACWAS) well field (well 41). The cause of this inversion may be active saltwater intrusion resulting in upconing from the MACWAS well field. This inversion is creating a broader mixing zone at the central portion of the island.

Critical observations from the island-wide observational model west–east perspective (Figure 5):

- Tidal forcing is evidenced along both west and east shorelines with resulting mixing zones exhibiting areas of passive saltwater intrusion.
- Hydraulic head data and associated freshwater lens morphology are similar to topography where the maximum amplitude of the hydraulic head is in a recharge area, central to the island and is affected by seasonal recharge dynamics, whereby the rainy season displays the more robust freshwater lens.

- Freshwater-saltwater mixing zone seasonal symmetry is evident throughout the two-dimensional profile. A broad zone of freshwater lens expansion is noted on the western boundary of the recharge zone in the former lagoon deposit area; however, this same zone illustrates a wide mixing zone between the two climate extremes presented in this data set (i.e. rainy and dry seasons).

Figures 4 and 5 demonstrate the integration of the FLAP attributes and the resulting island-wide observational model illustrations. Information from stakeholders creates an informed narrative on the role of anthropogenic stressors versus those which naturally occur, and their respective influence on water resources currently and, in some cases, into the future. Examples include: 1) the unmonitored pumping of groundwater along coastal margins for resort operations and the influence on saltwater intrusion in this vulnerable region of Bantayan; 2) the importance of maintaining freshwater lens recharge areas evident from the observational models presented; and 3) evidence of upconing due to over-abstraction activities concentrated at LGU well fields.

The combination of technical and social data sets forms the nexus for bringing technical and social information to multiple stakeholder groups, as presented in the island-wide observational model (Figures 4 and 5). Critical data collected in the field were analysed using commonly practised, well-documented, and proven theories and methods, and in some cases, empirically derived data sets were introduced to complete the model. Data types presented in Figures 4 and 5 represent its core elements and will serve as placeholders for targeting future data set requirements for effective management of a freshwater lens.

Island-wide observational model

In the context of this research, the island-wide observational model is intended to illustrate an actual system being researched. The intention of this model is to serve as a launching point for furthering constructive discourse between stakeholder groups on issues involving freshwater lens sustainability. Closely linked to actual data collected from the research, the model illustrates the progression of a basic conceptual model, as presented in Figure 2, with what can be achieved through the application of the FLAP.

The FLAP has brought together multiple data sets to advance a clearer picture of this natural system, in a compelling island-wide observational model intended to have a positive impact on the management of the freshwater lens. The island-wide observational model, therefore, becomes an island asset. The careful application of appropriate empirical data sets to complement local data sources was intended to minimize any potential uncertainty in the island-wide observational model, providing a complete image of the natural system, with wider utilization of the data sets by stakeholders. The model's limitations can be attributed to the frequent paucity and incompleteness of regional and local data sources. Despite this, this research provides stakeholders with an island-wide observational model, and guidance on the required data sets to take it forward.

Conclusions

Implications for practice and policy

The purpose of developing this assessment protocol is to provide a cost-effective, technically rigorous, non-invasive methodology for the development of an island-wide observational model that has sufficient relevance and accuracy to support local water resource management decision-making. It integrates quantitative and qualitative research methods into a holistic model. It also highlights how engagement with national, provincial, and local government was critical to ensure the research findings could be implemented through AWRM concepts.

As presented above, the FLAP is a set of technical and social methodologies applied to systematically advance a non-invasive hydrogeologic characterization and social scientific study to gain new understanding of water resource conditions on karst islands in LMICs. The value of this research does not rely on long-term, intense, academically driven studies. Instead, readily available locally derived data sets are appropriate to inform stakeholders on the mechanisms that contribute to saltwater intrusion, and how local stakeholders are adapting to this challenge.

Elements of the FLAP include:

- remote sensing imagery;
- well inventory survey;
- geo-hydrogeologic study;
- climate monitoring;
- water quality assessment;
- stakeholder engagement;
- island-wide observational model development.

The findings of this research offer empirical evidence that the FLAP can yield viable and compelling data sets about the characteristics of a freshwater lens beneath a karst island in an LMIC. An assessment of Bantayan Island in terms of its technical attributes of freshwater lens hydrogeology, the social elements derived from the attitudes and perspectives of multi-stakeholder groups on groundwater governance, and anthropogenic and natural stressors that influence the freshwater lens, yielded a rich data set that resulted in an island-wide observational model. This research furthers what is known about the implications for practice and policy discussed below.

Implications for practice

The FLAP that was developed and field-tested involved a complete and comprehensive examination of an island freshwater lens. The efficacy of the data sets assembled and analysed through this research is clear and compelling in successfully advancing the island-wide observational model for stakeholder use in managing the water resource. As a non-invasive instrument, the protocol systematically guides the research to gather the information necessary to assess both technical attributes and social aspects that influence a freshwater lens. As a characterization instrument, the FLAP has a clear and certain use for the advancement of hydrogeologic study of these island settings.

Implications for policy

This research highlights the need for transboundary engagement between the LGU on matters involving groundwater usage. Incorporating the hydrochemical data sets established in the FLAP offers a viable application for current groundwater monitoring policies at this level. Trained local field technicians could implement the actual field monitoring for physical parameters (pH, total dissolved solids, electrical conductance, and salts), utilizing the local monitoring network established for this research and continuing freshwater lens management. Sharing the data across government jurisdictions would open a dialogue regarding abstraction plans for the freshwater lens and introduce the holistic management approach endorsed by this research.

Evidence has been collected through geologic field mapping and remote sensing data sets to advance knowledge on the island geology, physiographic provinces, and its ability to influence the migration of salts in the freshwater lens of Bantayan Island. Study observations have been compared with empirical data sets for similar island regimes; the island-wide observational model developed presents a compelling representation of the geologic and hydrogeologic environments and their combined influences on freshwater lens dynamics and saltwater intrusion.

A significant contribution to literature is made in the integration of quantitative and qualitative data sets into the development of an island-wide observational model of a karst island, and in how the data sets influence the migration patterns of salts entering the freshwater lens. Findings from this research align with the work of Werner and Simmons (2009), where identification of these variables and their implications for freshwater lens sustainability is vital to stakeholder application of this knowledge. The model presented will serve as a starting point for stakeholders to acknowledge the risks and their roles in mitigating the deterioration of their water resource. Moreover, the output from this research has been delivered through workshops to the LGUs to strengthen the capacity of relevant stakeholders and to ensure the research output was implemented for the benefit of the citizens of Bantayan Island.

The research challenges were overcome through engagement with local experts and access to local data sets. Establishing a strong local network of resources is integral to the success of a FLAP. In contrast, in-depth analytical modelling of the hydrogeology is not required for its effective application as it is informed by local data sets and an understanding of stakeholder attitudes regarding water resources in their communities. The goal of this research was to be translational to local stakeholders to improve capacity and understanding of freshwater lens management. This was demonstrated by the local stakeholder workshops conducted at the close of the research. These dissemination and communication activities are vital mechanisms for knowledge exchange to improve understanding of this fragile water resource.

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