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Assessment of groundwater resources: Nauru project 2010 – 2019

Valutazione delle risorse idriche sotterranee: progetto Nauru 2010 - 2019

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Riassunto: Nauru è una piccola isola calcarea nella regione del Pacifico dove, come in molte piccole isole del mondo, la popolazione fa molto affidamento sulle acque sotterranee come risorsa primaria di acqua dolce, in combinazione con l'acqua piovana e l'acqua desalinizzata. Il progetto Nauru, avviato nel 2010 e guidato dal Politecnico di Milano (http://nauru.como.polimi.it/), consisteva nella caratterizzazione idrogeologica della parte settentrionale dell'isola e nell'implementazione di 3 modelli numerici per: (1) comprendere i meccanismi che regolano il flusso e l'accumulo dell'acqua dolce, (2) stimare lo sfruttamento sostenibile delle acque sotterranee, nell'area più adatta per l'estrazione, al fine di prevenire gli eventi di *upconing* e (3) simulare scenari futuri basati sui cambiamenti climatici e sulla crescita demografica.

Abstract: *Nauru is a small limestone island in the Pacific region where, as in many small islands in the world, the population heavilyrely upon groundwater as primary freshwater resource, in conjunction with rainwater and desalinated water.The Nauru project started in 2010 and led by Politecnico di Milano (http://nauru.como.polimi.it/), consisted on the hydrogeological characterization of the northern part of the island and the implementation of 3 numerical models for: (1) understanding the mechanisms governing groundwater flow and accumulation, (2) assess the adequate sustainable fresh groundwater exploitation in order to prevent saltwater upconing occurrences in the area more suitable for groundwater extraction and (3) to simulate future scenarios based on climate changes and population growth.*

Keywords: *groundwater management, numerical modeling, hydrogeological characterization, small islands.*

Parole chiave: gestione delle acque sotterranee, modellazione numerica, caratterizzazione idrogeologica, piccole isole.

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Introduction

Groundwater systems in small islands generally occurs as freshwater lenses overlying denser seawater. They areoften the only permanent sources of freshwater for island's ecosystems and humancommunities.In the Pacific region, aquifers are under pressure from growing populations, climate change and climate variability (Holding et al. 2016). Meanwhile, knowledge of the response of freshwater lenses to sea level rise, seawater movement and environmental pressures is still limited (White and Falkland 2011; Dixon-Jain et al. 2014).

Nauru is a small limestone island with a surface area of 22km² and homes to about 10.000 people. Groundwater is an important freshwater resource for Nauru, which has no surface water and relies heavily on groundwater, in conjunction with rainwater and desalinated water (Bouchet and Sinclair 2010). Most of the population lives along the coastline where approximately 50% of houses access groundwater through private wells. The coastal aquifer is small and thin and salinity levels varies throughout the year, from fresh to brackish, depending on rainfall and extraction. The resource is also largely polluted from poor sanitation systems and not deemed safe to drink without prior treatment. Despite its low quality, groundwater is heavily relied upon and households with a reticulated access to groundwater tend to use it for most of their needs (i.e. 83% of water use). Groundwater is thus a vital source of water for Nauru and its use has been steadily increasing in the past 50 years (Bouchet and Sinclair 2010).

Several hydrogeological studies have been conducted on Nauru, but only a few of them have been published (Alberti et al. 2017). Past hydrogeological studies have focused on finding freshwater reserves that could provide part of the island freshwater supply (Ghassemi et al. 1996; Jacobson and Hill 1988; Falkland 2009). Jacobson and Hill (1988) suggested the existence of two small freshwater lenses in the centre of the island (blue meshed areas in Figure 1), which Politecnico di Milano initially decided to investigate for a groundwater supply project.

The Nauru project started in 2010, led by Politecnico di Milano in collaboration with the Nauru Rehabilitation Company (NRC) and Ministry of Commerce, Industry and Environment (CIE) with a focus to assist Nauru in sustainably develop its groundwater resources. Based on the findings from Jacobson and Hill (1988), the project originally aimed at exploiting groundwater resources from the central plateau. However, further investigations revealed that the two freshwater lenses previously identified below the central plateau were observed during a relatively high rainfall period and did not exist during periods of low rainfall (Falkland 2009; Alberti et al. 2017). It is now believed that the small island size, coupled with the high conductivity and karstified nature of the limestone, does not allow the formation of any substantial freshwater lens on the island interior (Falkland 2009). The project focus thus changed, as more hydrogeological investigations were needed to ascertain if there was any substantial freshwater lenses in Nauru. Starting from the data available in previous studies, the hypothesis arose that freshwater accumulates in the sandy part of the island, close to the coastline. The intent of the project was then to further improve the conceptual model of the island and verify the hypothesis of freshwater storage, to evaluate where more resilient fresh groundwater lenses were present and, accordingly, address groundwater extraction in the more feasible zones.

From 2010 to 2018, the project included three hydrogeological field investigations assisted by regular groundwater monitoring from NRC and CIE. Further work included the development of three numerical models to better understand the local water balance and salt intrusion mechanisms and to quantify the impact of future climate on the resource and associated sustainable yield of groundwater extraction. This short notesummarises the activities and results of the project, from 2010 to 2019.

Material and methods

The first phase of the groundwater investigation undertaken by Politecnico di Milano consisted inthe characterization of the island groundwater regime. This included:

- A photogrammetric survey to developa Digital Terrain Model (DTM);
- A review of subsoil data from 127 geo-referenced wells present in the island to define the geological setting of the island;
- A piezometric survey allowing to understand the tidal influence on groundwater level and associated spatial distribution and tidal lag;
- Several electro-conductivity surveys in the island monitoring network and private wells
- A series of pump tests and slug tests;
- A geo electrical investigation.

The island characterisation activities revealed that the largest volume of freshwater is present in the northern part of the island where wells S1 and S18 are located (Fig. 1). To further understand the recharge and flow of groundwater in this area, a 2D steady state model was first developed using the MODFLOW/SEAWAT finite difference codes (Harbaugh 2005; Langevin and Guo 2006). The 2D model was used as apreliminary study prior to implement thefull 3D model. The model was calibrated in accordance to the head and concentration data collected in 2010 in private and monitoring around the targeted area (Alberti et al. 2017). The sensitivity analysis showedthat the model is highly influenced by horizontal hydraulic conductivity and dispersivity. Considering that tidal effects can produce considerable impacts on seawater intrusion processes in mixing zones (La Licata et al. 2011), the model was primarily calibrated based ondispersivity and hydraulic conductivity values.

Following the model calibration, the second part of the study focused on the freshwater lens characterization, for further development of groundwater infrastructures for water withdrawal (Fig. 1). Additional groundwater field investigations were performed to quantify the freshwater lens thickness and volume while the modelling activities focused on coastal monitoring wells (S1-S18) to understand the mechanisms allowing freshwater to accumulate in this area. An unsteady state 3D model was then implemented, using the MODFLOW/SEAWAT finite difference codes, for a comprehensive understanding of the system behaviour and to assess the adequate sustainable fresh groundwater exploitation to prevent saltwater upconing occurrences. This model has the capability to provide important information for the design of new suitable groundwater abstraction systems (infiltration galleries), also assessing their impacts on fresh groundwater availability and quality (in terms of salt concentration) under different stress conditions and then supporting public decision-makers in setting up plans to fulfil the goal of a sustainable groundwater management.

Finally, to understand how future climate and human pressures will affect groundwater resources in Nauru the study investigated the impact of abstraction, drought and future climate on groundwater storage. To do so, a new 3D numerical model was implemented using now FEFLOW 7.0 code (Diersch 2014) in order to better represent the position of the wells along the coast. A series of simulations were performed (scenario testing) using future population projections (RON 2011), climate predictions (BOM and CSIRO 2014), historical rainfall data (RON 2017) and current abstraction scenarios.

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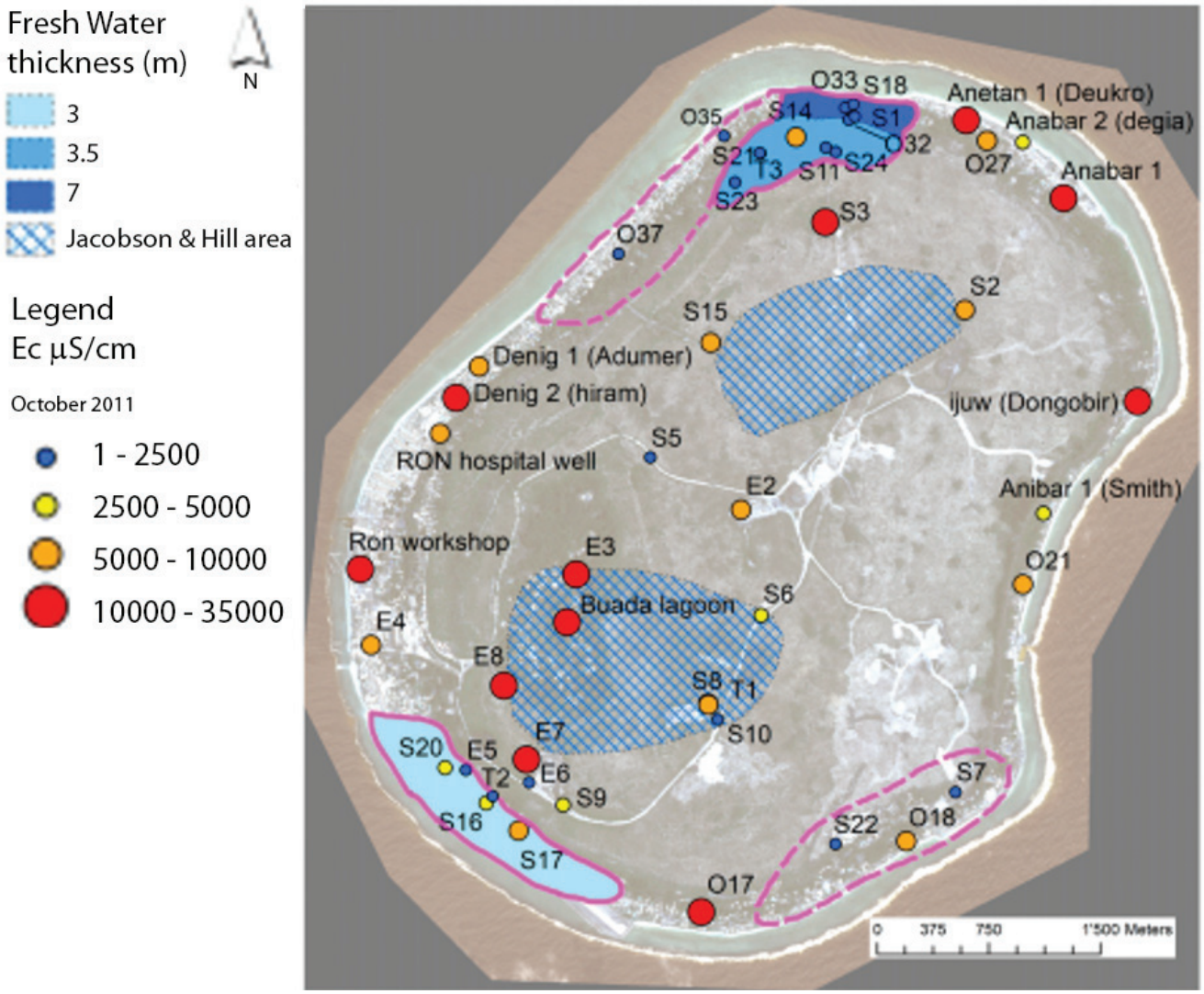

Fig. 1 - Results of the EC survey in monitoring wells (October 2011). Pink line indicates the most suitable areas for groundwater exploitation and the pink dashed one the potential suitable areas.

Fig. 1 - Risultati della campagna di conducibilità elettrica (EC) sui pozzi di monitoraggio (ottobre 2011). La linea rosa indica le aree più idonee allo sfruttamento della falda acquifera mentre la rosa tratteggiata le aree potenzialmente idonee.

Results

Results from the investigations conducted in the last nine year in Nauru reveals that the coastal belt consists of homogeneous sandy sediments present until about 5 m from the ground. Below these sediments are carbonate rocks, as documented by Jacobson and Hill (1988), which are present also in the central part of the island.

The 2D model results highlightedthat the transition from the central limestone to the coastal sands is responsible for the freshwater storage mainly observed in the northern zone of the island. In particular, the hydrogeological investigations and the calibration process of the mathematical models have highlighted that the coastal zone, filled by sands, is the one where the largest thickness of freshwater occurs. This is because the hydraulic conductivity of this area, smaller than the limestone internal zone, allows the flow to slow down and the groundwater to store.

The geoelectrical investigation allowed quantifying the volume of freshwater amount in the northern part of the island. An estimated 45,000 m^3 of fresh groundwater is present in this aquifer. This amount of groundwater could be sustainably exploited to benefit a larger population and to reduce the desalting plant operation. Sustainable yield of extractions were tested using the 3D numerical model to evaluate how to prevent saltwater upconing occurrences (Castelletti et al. 2012).

The climate change scenarios results, from FEFLOW simulations, showed that groundwater salinity generally increases as the sea level rises and decreases as the meteoric recharge increases, as might be expected. However, the results showed a strong correlation between concentration and recharge values, while less dependent on sea level variations (Fig. 2).

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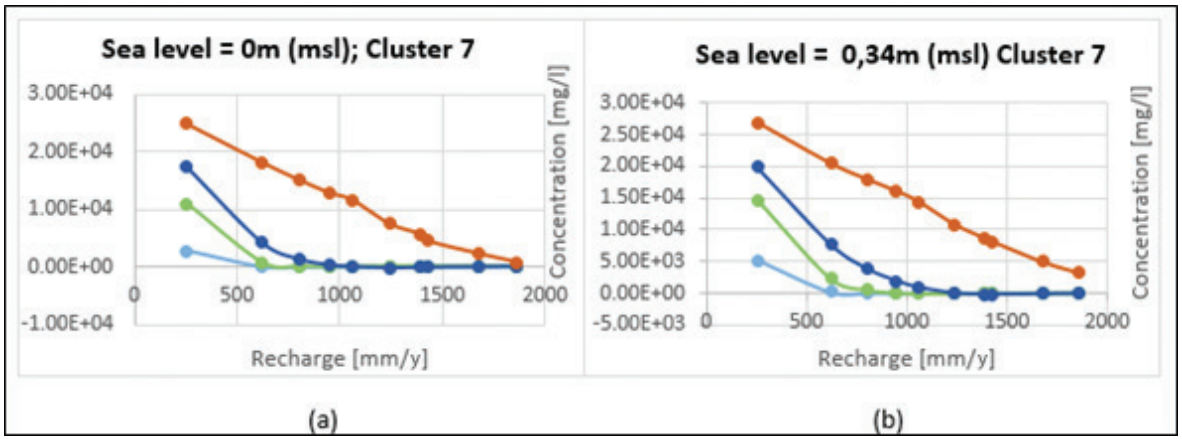

Fig. 2 - Change in concentration for various recharge scenarios in the monitoring well S1 (cluster 7). (a) for the current sea level and (b) for the highest sea level scenario of 0.34 m a.s.l.. Each coloured line represents a different depth in the well: light blue = 2 m; light green = 3.7 m; dark blue = 5.3 m; orange = 10 m

Fig. 2 - variazione della concentrazione per vari scenari di ricarica nel punto di monitoraggio S1 (cluster 7). (a) per l'attuale livello del mare e (b) per lo scenario più alto del livello del mare pari a 0,34 m s.l.m. Ogni linea colorata rappresenta una diversa profondità nel pozzo: blu chiaro = 2 m; verde chiaro = 3,7 m; blu scuro = 5,3 m; arancione = 10 m.

In sandy deposits, especially in the Northern area, the presence of a fresh water lens is detected in all simulations, regardless of the changing values used. In this sector (S1, S18), the current depth to which freshwater is observed (concentration below the threshold of 1500 mg/L suggested by WHO) averages 7 m. The results showed high variations in freshwater thickness, from a total thickness of 1 m (2-year drought) to 13 meters (highest average recharge scenario). In this area, as already observed by Alberti et al. (2017), the reduced hydraulic conductivity of sandy sediments leads to a greater inertia of the system to the stresses imposed and the consequent accumulation of fresh water. Under the extreme 2-years drought scenarios however, the lens thickness is reduced to 1 m, which will highly limit extraction. In general the prediction results are:

- The lens will increase in average thickness;
- The lens is likely to be vulnerable to long drought periods;
- The general trend for the next 30 years indicates an unexpected freshening of the aquifer;
- Drought will remain a threat although shorter drought will have lesser impact;
- During drought periods, groundwater abstraction can quickly create saltwater.

Conclusion

Over the past decade, groundwater investigations in Nauru have allowed to better comprehending groundwater resources in the island and helped identifying the key mechanisms for groundwater storage offering insight for groundwater management.

Groundwater investigations have clearly demonstrated that the largest volume of freshwater is present in the northern part of the island. Modelling activities have been focused on coastal monitoring wells in this zone to understand the mechanism that allows such a storage. The implemented finite differences 2D and 3D models allowed identifying the transition from limestone to coastal sand which permitfreshwater accumulation close to the seashore. The monitoring activities, carried out for a 8-years period, have moreover highlighted that these lenses are resilient to average drought conditions.

Finally, the geoelectrical investigation allowed quantifying the freshwater amount in the northern part of the island that could be sustainably exploited in order to redistribute the water resource basing on population needs or reduce the desalination plant operation.

Further research has allowed understanding the impact of climate change and growing populations on groundwater availability using a 3D finite element model implemented using FEFLOW. Prediction results reveal that the lenses will increase in average thickness but they will still be vulnerable to long drought periods. The general trend for the next 30 years indicates an unexpected freshening of the aquifer which will become more resilient to low rainfall periods, where recharge is highly reduced. The project will further investigate the most suitable technology (infiltration galleries) to provide sufficient water for the surrounding districts and sustainable yield.

Further understanding of the coastal aquifer will be beneficial to assist the government in mapping groundwater resources, which will provide opportunities to develop small-scale abstraction and help households better design private wells. Increased community engagement is also essential to share the knowledge gathered during the project life and gauge interest from local communities and government alike for the development of groundwater extraction projects.

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