Utilization of Reclaimed Island as Groundwater Reservoir

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ABSTRACT

In view of current shortages of land and freshwater, it is proposed to make a reclaimed island, designed to be dedicated to industrial use, also serve another purpose- as a functional groundwater reservoir. The groundwater would ensure self-reliance for the industry on the island to meet its water demands locally. The hydrogeology and groundwater dynamics of Jurong Island, offshore Singapore mainland, are studied in details using field data and computer models. The results offer encouraging results regarding storage potential of the aquifer found in the island. Saltwater intrusion and subsidence risks have been evaluated and can be considered manageable. Computational scenarios were simulated to evaluate different extraction and recharge mechanisms and estimate extraction efficiencies. The study comprehends typical processes involved in the development and maintenance of an artificial aquifer and can be used as an example for future reclaimed island aquifers.

INTRODUCTION

Land reclamation near coastal areas is increasingly being used in to solve land scarcity problems. From the 1970s onwards, countries in Asia like Singapore, Hong Kong, Taiwan and Japan decided to build land reclaimed from the seabed for urban use. Artificial islands arising from reclamation works, such as Jurong Island in Singapore and Maasvlakte II in Rotterdam are dedicated to industrial use. Coupled with the shortage of land, is the increasing demand for water. Rapid urbanization and industrialization threatens available fresh water quantity and quality. Extraction of groundwater is a viable solution. However, groundwater extraction at coastal area is prone to saltwater contamination. Vertical and lateral saltwater intrusion could render the well unusable. However, this risk could be controlled by knowledge on the local groundwater system and active management of recharge and extraction. Excessive extraction could lower the pore water pressure and increase effective stress and subsequently cause subsidence.

This has resulted in concepts like Artificial Storage and Recovery (ASR), a frequently used sustainable water management option, in which surplus water is stored in the aquifer for future use (van Ginkel, 2015). The reclaimed artificial islands are especially suited for the application of this concept, provided the hydrogeology of the island is appropriate. It can be considered prior to the development of such islands what kind of sediments should be used in case it has to be used as an aquifer later. The materials used for land reclamation can be sandy and gravel which has good hydraulic conductivity and porosity. If the island has industrial purposes, the water demands can be met using the local aquifer reservoir.

Although an aquifer in Jurong Island was not intended initially, hydrogeology of Jurong Island has been studied and found viable as an Artificial Island Storage and Recovery

(AISR) concept (Tijs, 2014), with a sandy aquifer underlain by clayey, coral deposits and granite formation. 3D models of the subsurface lithology and groundwater flow have been simulated based on geophysical survey and monitored data. Saltwater intrusion was studied through computer simulation. A subsidence model was also created to assess the risk of subsidence in relation to groundwater extraction.

The implication of the use of reclaimed land as underground water reservoir is promising. When the associated risks are managed properly, it could mean a reliable water resource, with minimal surface footprint and reduced evaporation losses.

METHODS

Concept

The development of freshwater lens on a newly reclaimed land at the coast starts with only saltwater in the aquifer. With continuous natural recharge from rainfall, freshwater infiltrates the ground, pushing the subsurface saltwater downwards and sideways, forming a groundwater lens. In the beginning, the rate of growth of freshwater lens is dependent on recharge rates and volumes available from rainfall. The rate depends on the hydraulic conductivity of the material used for land reclamation. Land cover should not be a limiting factor at this stage, as the land is usually left vacant to enable settlement of land for a few years before any developments begin. With recharge, the freshwater lens grows until it reaches equilibrium with brackish water underneath and around (Oude Essink, 2001). The shape of this freshwater lens is dependent on the geometry of the island, as well as the lithology while the amount of storage is a function of thickness of landfill layer and storativity.

Case study – Jurong Island

Jurong Island is made up of seven original islands, combined through land reclamation at two different phases. The bedrock elevation varies between -17 to -45 m with an average elevation of -35 m below the present ground surface. This bedrock serves as the hydrogeological base for the aquifer. The sandfill layer is estimated to be 9 to 24m thick, with the thickest landfill layer at the western part of the Island. This subsurface configuration affects groundwater directly, determining geometry of the aquifer and the spatial variability on fresh groundwater depths. Due to the thickness of the landfill layer on western part of the Jurong Island, the freshwater lens was found to be the thickest.

The development of freshwater is also time dependent. Jurong Island was reclaimed on phase in different years (Figure 1a). This has resulted in the current fresh-salt distribution of the groundwater, the calculated total fresh groundwater volume in 2015 (~30 Mm3) and the depth of the freshwater lenses.

Recharge and extraction strategies

Groundwater extraction is not without risk. Excessive extraction of groundwater can result in salt-water intrusion and land subsidence. Saltwater intrusion, either vertical (upconing) or lateral, could be prevented by dynamically managing groundwater extraction and recharge. Land subsidence, which is caused by excessive extraction could be minimized by understanding the lithology and characteristics of the surface and subsurface materials on Jurong Island. With these two risks in mind, an effective recharge and extraction strategies on this reclaimed land is important.

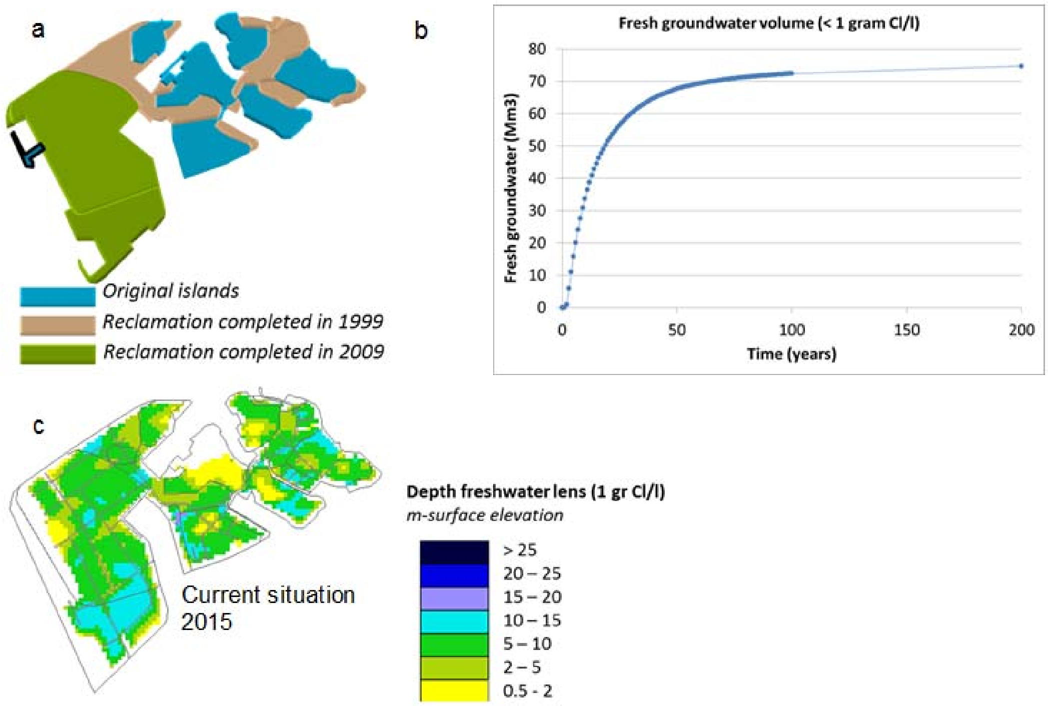

Figure 1 a. Development of Jurong Island in time; b. calculated fresh groundwater volume with initial concentration 18gr Cl/l. and c. calculated depth freshwater lens taking into account the development of the island.

Recharge strategy

Managing natural or artificial recharge is essential in groundwater management, as this directly affects the sustainable extraction rate by preventing saltwater intrusion. On Jurong Island, the permeability of the reclaimed sandfill layer is quite high (up to 159 m/day), with spatial variability, making it suitable for infiltration. In addition to the recharge from rainfall, which will be reduced when the island is industrialized it can be considered to artificially introduce water into the aquifer. The aquifer is shallow and for higher extraction efficiency it is better to recharge and let the freshwater lens deepen. Incorporation of groundwater recharge strategy in early planning phase is thus important. In the Jurong Island groundwater study, scenario analysis shows the effect on aquifer yield due to artificial recharge. The scenario considers infiltration using the drainage system as an effective recharge strategy.

Extraction strategy

Good extraction strategy could not only improve the extraction rate, it could help to minimize land subsidence. Horizontal wells or horizontal drilled directional wells (HDDW) are more effective for shallow aquifers. Horizontal well will reduce the drawdown and buoyancy effects at one single location and, thus, improve the amount extractable. Towards the beginning, as the freshwater lens is still relatively shallow, it is useful to explore the use of scavenger well (Zuurbier, Kooiman, Groen, Maas, & Stuyfzand, 2014). The scavenger well is a two-tier extraction well with one extraction took place in freshwater zone and one in saltwater zone. This design helps to minimize the saltwater intrusion due to local upconing. Efficiency of impermeable barriers to stop lateral intrusion during extraction was also evaluated. Extraction strategy could be used in conjunction with right recharge strategy to improve extraction rate. The location of the recharge and extraction infrastructures, in relation to the freshwater depths and distance from the coasts also play a significant role.

In Jurong Island study, computational scenarios were performed to examine the efficiency of different well configurations. The highest sustainable rate was obtained using the combination of horizontal well and artificial recharge using the drainage system. Land subsidence was found to be minimal (less than 1mm). In practice, the extracted freshwater can be used in the local industry on the island.

CONCLUSIONS

The reclaimed Jurong Island provides a good opportunity to be developed into a functional groundwater reservoir that can potentially serve the industrial water demand in the island in a self-reliant manner. This study can serve as an example to identify such potential across other reclamation works, and identify possible timeline of freshwater lens development and steps to harness it. The recharge and extraction should be actively managed. Artificial recharge at strategic locations will improve the future yield in combination with extraction frameworks such as the use of scavenger wells and horizontal wells. Good groundwater management strategy could help to minimize saltwater intrusion and subsidence risks.

KEYWORDS: groundwater reservoir, ASR, reclaimed land, salinisation, land subsidence

REFERENCES

Oude Essink, G. H. (2001). Improving fresh groundwater supply—problems and solutions. *Ocean & Coastal Management*, **44**(5-6), 429–449. doi:10.1016/S0964-5691(01)00057-6

Tijs, M. L. (2014). *Subsurface freshwater storage and recovery in artificial islands*. M.Sc. thesis, Delft Unniversity of Technology, The Netherlands

Van Ginkel, M. (2015). Aquifer design for freshwater storage and recovery in artificial islands and coastal expansions. *Hydrogeology Journal*, **23**(4), 615–618.

Zuurbier, K. G., Kooiman, J. W., Groen, M. M. a., Maas, B., & Stuyfzand, P. J. (2014). Enabling successful aquifer storage and recovery (ASR) of freshwater using horizontal directional drilled wells (HDDWs) in coastal aquifers. *J. Hydrol. Eng.*, **20**(3), B4014003

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