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Modeling Investigation of the Underground Dam on Samui Island, Southern Thailand

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ABSTRACT: Samui island in southern Thailand has become an ever-increasingly attractive tourist spot over the last decades. It is thus of no doubt that water deficit, mainly, during the tourist season – the main source of water is surface water stored in a few reservoirs across the island - has become more severe in recent years. Department of Groundwater Resources (DGR) has been aware of this problem and has thus initialized induced the project of underground groundwater dam to better manage the groundwater resources on Samui island which is supposed to impede the natural groundwater outflow towards the sea and so to increase the usable groundwater storage during the dry season. Based on results of a comprehensive hydro-geological field analysis that included geophysical surveys as well as drilling and piezometric monitoring, the aquifer system can be discriminated as a three-layer aquifer with, from top to bottom, i.e., (1) the sand-clay unconfined aquifer, (2) the sand-clay confined aquifer and, (3) the weathered granite-confined aquifer. The dam will be realized by two on a central impervious rock abutting low-permeability-, groundwater-flow-impeding walls that cut through the three layers of the aquifer system, down to a maximum depth of about 50 m. A top of the 2 m in width of dam, which ends below the upper, unconfined aquifer layer, a vertical layer of high permeability will be set up, so that a “spillway-like” over-flow of the groundwater is enabled, in order to not disturb too much the subsurface ecology downstream. According to above data, a 3D numerical groundwater flow model with areal domain of 11.5 km x 7.5 km have been, respectively, conceptualized, set up and calibrated in both steady and transient mode. The computed head is good agreement with the observed head. In the subsequent modeling analysis the underground dam with the spillway characteristics as mentioned above has been embedded into the model by specifying the corresponding vertical curtains of low and high conductivity, respectively. Finally, groundwater pumps upstream of the underground dam have been included into the model. Simulations without and with the hydraulic structures have been performed to ascertain the differences with respect to groundwater levels and -storage and to evaluate the overall functionality of the underground dam. The results show that the underground dam is able to raise groundwater levels, i.e. raise the groundwater storage. The budget analysis of the simulation sets indicates that the underground dam serves well its purpose, particularly, for long dry spells, as more groundwater can be pumped out of aquifer system than would be possible without such a hydraulic structure.

Keywords: Groundwater Flow Modeling, Underground Dam Design, Samui Island, Southern Thailand

1 INTRODUCTION

Koh Samui island, in the province of Surathani in southern Thailand has become an ever-increasingly attractive tourist spot over the last decades, attracting thousands of visitors each year, especially, during the winter season. It is therefore of no surprise that water shortages, mainly, during the tourist season – the main source of water is surface water stored in a few reservoirs across the island - have become more and more frequent in recent years, accentuated, not to the least, by regional climate change. The scarcity of surface water during the dry season has led to the emergence of new water vendors that withdraw (partly illegally) groundwater and sell it to water consumers at an expensive price. The Thai Department of

Groundwater Resources (DGR) has been aware of this problem and has thus initialized first steps to better manage the groundwater resources on Koh Samui island.

One recently endeavored new project to improve this water scarcity situation will be the construction of an underground groundwater dam which is supposed to withhold the natural groundwater outflow towards the ocean and so to increase the usable groundwater storage during the dry season. For this reason, a feasibility study of the construction of such underground dam on Koh Samui island has been initiated. One of the tasks to be completed as part of this investigation and which is the focus of the present paper, is 3D groundwater flow modeling of the effects and suitability of the underground dam proposed.

Underground dams designed to intercept or obstruct the natural flow of groundwater through an aquifer towards an outflow constant head boundary, for example the sea, and so to provide storage for groundwater, have been known for some time to be particular useful in regions with arid or tropical climates with large seasonal hydrological variations (e.g. Hansson and Nilsson, 1986; Nilsson, 1988). Underground projects have been realized in the southwestern states of the United States, in Brasil and, especially, in southern India (Nilsson, 1988). In Thailand a feasibility study for the construction of an underground dam on Phuket island has been carried out by Das (1998), but is yet to be realized.

2 STUDY AREA

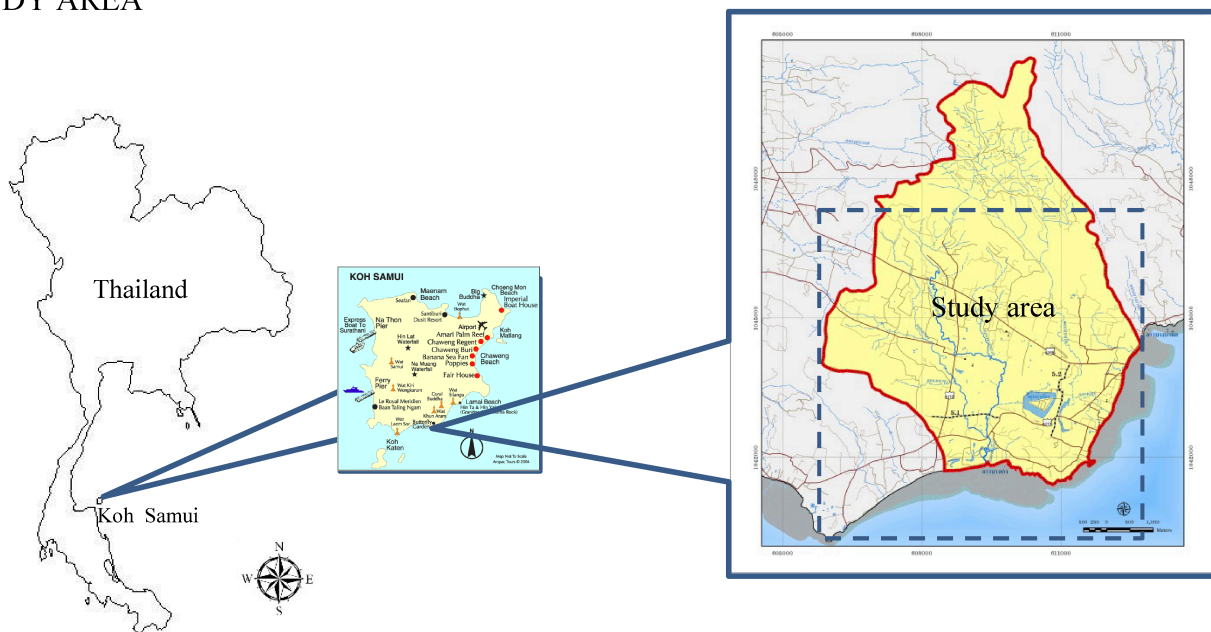


Figure 1. Study area on Samui island, Southern Thailand, with outline of FD grid

The study area is located in the southeastern part of Samui island, between two sub-parts, called “Aao Bang Kao” and “Aao Bang Nam Jued”. The study area has a size of about 85 km² and includes the Plu Na Muang reservoir for the public water supply, 19 inland canals that are connected with the sea in the southeastern part of study area.

The aquifer system, called here the “*Samui-underground dam aquifers*” or “*SUD aquifers*”, consists of 3 layers, namely, (a) the upper sand-clay unconfined aquifer (it’s thickness is about 10 meters), (b) the sand-clay confined aquifer and (it’s thickness is about 10 meters) and (c) the weathered granite confined aquifer (it’s thickness is about 40 m) (see Fig. 2).

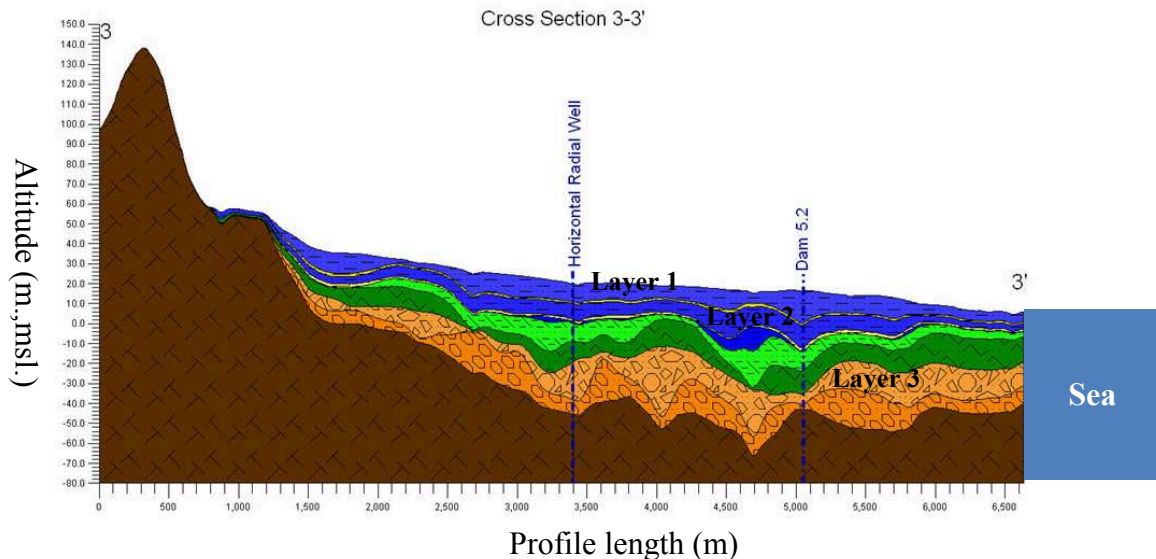


Figure 2. Hydro-geological profile underneath the study area indicating the aquifer system: unconfined aquifer (1st layer), sand-clay confined aquifer (2nd layer) and weathered granite aquifer (3rd layer).

3 MODEL IMPLEMENTATION

3.1 Conceptual model for the SUD aquifer system on Koh Samui island

The conceptual 3D - groundwater model for the SUD-aquifer systems is conceptualized based on its major hydrogeological and physical characteristics and its embedding in the regional hydrological cycle. That is, the conceptual model is set up using the geological data, geological descriptions, hydrogeology, hydrology, topography, groundwater extraction rates, soil conditions and land uses, some of which has recently been collected by Thai DGR (Department of Groundwater Resources) (DGR, 2010).

The conceptual model of the SUD- aquifer system, as implemented later in the MODFLOW 3D groundwater flow model (McDonald and Harbaugh, 1984), is presented in Fig 3. Based on the geological information of Fig. 2, the SUD- aquifer system is set up with three aquifer layers, namely, an upper sandy-clay unconfined aquifer, followed by a sandy-clay first confined aquifer and finally, a second weathered granite confined aquifer. The aquitard layers between the aquifer layer are not explicitly included in the model and only specified in terms of their leakage rates, which are implicitly computed in MODFLOW based on the differences of the hydraulic conductivities in the adjacent aquifer layers (eg. Arlai et al., 2006; 2012; Arlai, 2007).

Neumann no-flow boundary conditions (BC) are specified at the ridges of the mountains (acting as symmetry boundaries) encompassing the basin and also at the bottom of the aquifer system which is underlain by crystalline rocks. The seawater boundary of the model is represented by a Dirichlet-BC of constant heads ($h=0$). The MODFLOW-river package is used to simulate the interaction mechanisms between the 19 canals and underlying groundwater system, whereas the model's reservoir package is used to specify the interaction between the Plu Na Muang reservoir and the aquifer system. Finally MODFLOW's recharge package is enabled to represent the basin's natural recharge from precipitation, whose exact amount is determined during the calibration process presented in the subsequent sub-section.

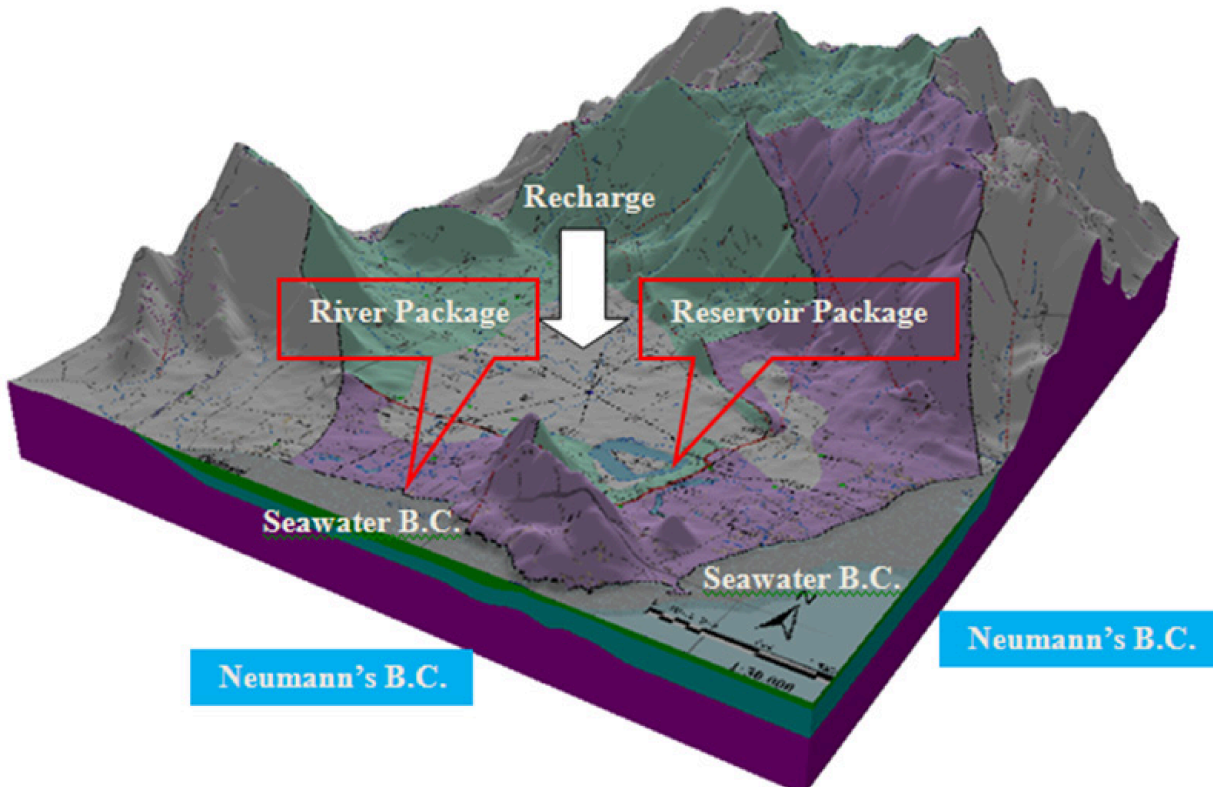


Figure 3. Conceptual model of the SUD aquifer system with boundary conditions and MODFLOW- packages enabled to represent the surface-groundwater interactions

3.2 Groundwater flow model set-up and calibration

Following the build-up of the conceptual model for the SUD aquifer system, the 3D finite difference (FD) MODFLOW groundwater flow model (McDonald and Harbaugh, 1988) is set up in the Visual MODFLOW[®] environment. The boundary- and external forcing conditions as indicated in Fig. 3, together with the corresponding packages are applied to the groundwater model.

Prior to a detailed calibration of the model, the size of the optimal horizontal grid i.e. the optimal number of horizontal grid points in the aquifer system is determined, wherefore the same grid structure for all three aquifer layers is assumed. Doing so not only avoids unnecessary small grid sizes, i.e. excessive simulation times, but also discourages the use of very different widths and lengths of the elements of the FD-grid which should be avoided to reduce discretization errors in the numerical approximation (e.g. Anderson and Woessner, 1992; Domenico and Schwarz, 1998, Arlai et al., 2012).

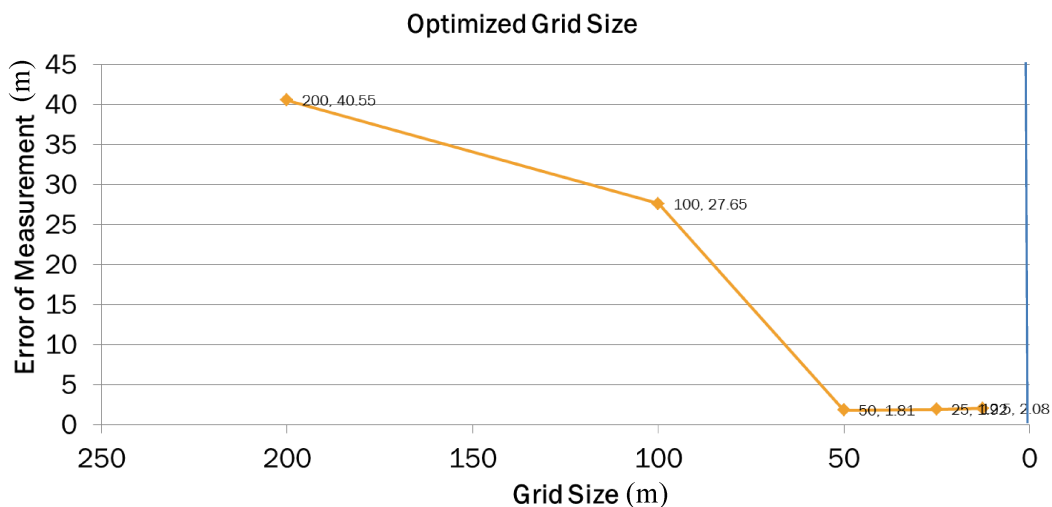


Figure 4. RMSE (root mean square error) versus grid size (m) for the SUD-aquifer MODFLOW model.

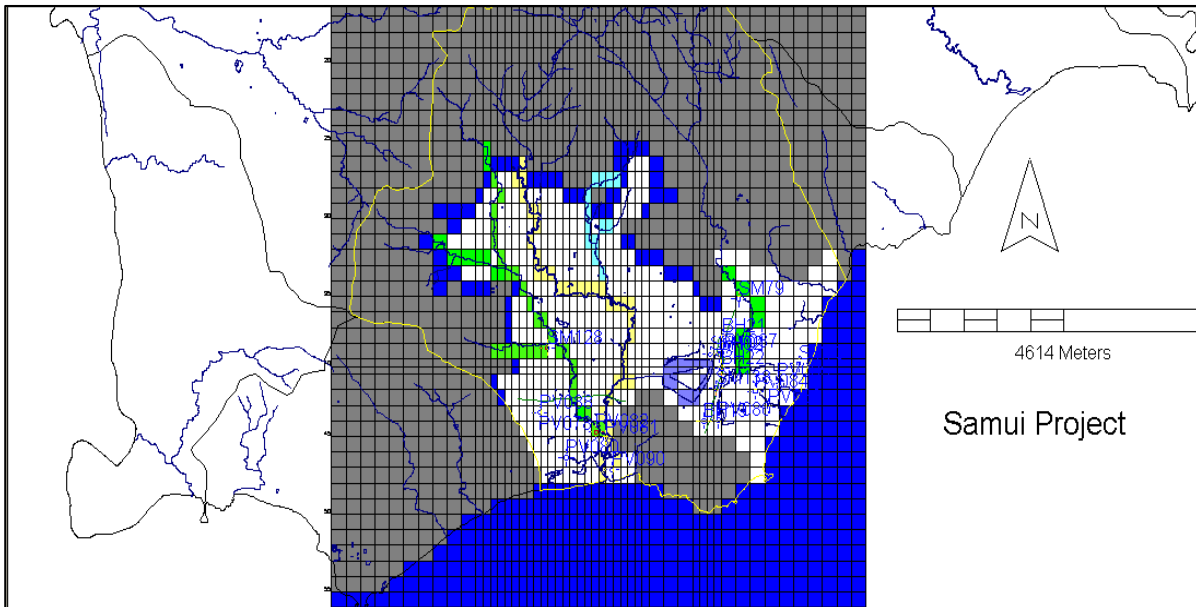


Figure 5. Finite difference grid of the SUD groundwater model with active (white) and inactive (gray) cells. Blue cells mark the sea as well as boundaries where a Dirichlet boundary is specified. Yellow, green and turquoise-colored cells delineate natural canals or creeks, as specified in the river boundary package. The reservoir, specified by the reservoir package, is indicated by gray-blue colored cells.

The results of this analysis are shown in Fig. 4 which indicates that the optimal horizontal size of the grid elements is about 50m x 50m, i.e. no noticeable further reduction of the RMSE is obtained when smaller grid elements are used. The final FD grid used in the subsequent computations is shown in Fig. 5, which also reveals the cells that are activated by the various MODFLOW packages discussed earlier.

The calibration of the SUD groundwater model is carried out in both steady-state and transient mode, with the objective to ensure that the model can reasonably well mimic the groundwater flow system, namely, fit the observed piezometric heads. The latter were measured at 46 monitoring wells that were installed by DGR during 2009 and the beginning of 2010. The measurement period available in the present study goes from April, 2009 to March, 2010.

In the steady-state calibration process the horizontal and vertical hydraulic conductivities K_{xy} and K_z , respectively, in the three aquifer layers as well as the groundwater recharge are adjusted in a trial and error manner, while in the transient calibration the storage parameters, i.e. specific yield S_y for the upper, unconfined aquifer layer and storativity S for the two confined layers are adjusted in addition.

Fig. 6 shows, as an example of the steady-state calibration, the scatterplot of the modeled and observed piezometric heads in the 2nd (confined) aquifer layer. The root mean squared error (RMSE) of the fit of the observed heads by the model in this 2nd layer is 1.73m, whereas values of 1.73m and 1.55 are obtained in the 1st and 3rd layer, respectively. The ratio of the RMSE to the regional head difference Δh which measures the maximum difference between upstream- and downstream head in the model domain, $RMSE/\Delta h$, varies between 3.47 and 4.20%. As a ratio of < 5% is commonly considered as acceptable (Anderson and Woessner, 1992), the results of the steady-state calibration are to be judged as satisfactory.

Regarding the calibration parameters, i.e. the hydraulic conductivities, the optimal K_{xy} in the three layers are found to vary between 1 and 21 m/day, whereas K_z are about 1/10 K_{xy} . Finally the calibrated groundwater recharge is 155 mm which amounts to about 10 % of the annual rainfall in the study area.

As a result of the transient calibration, an optimal specific yield S_y of 0.08 is obtained for the 1st (unconfined) aquifer layer, and storativities S of 5×10^{-5} and 3.54×10^{-5} in the 2nd and 3rd (confined) layers, respectively. The monthly calibrated recharge is found to vary between zero and 4.12×10^{-3} m/day.

In a final step the volumetric budget of the calibrated SUD groundwater model has been checked. A discrepancy of less than 0.01 % for the former is found, which provides some additional confidence on the quality of the calibrated model.

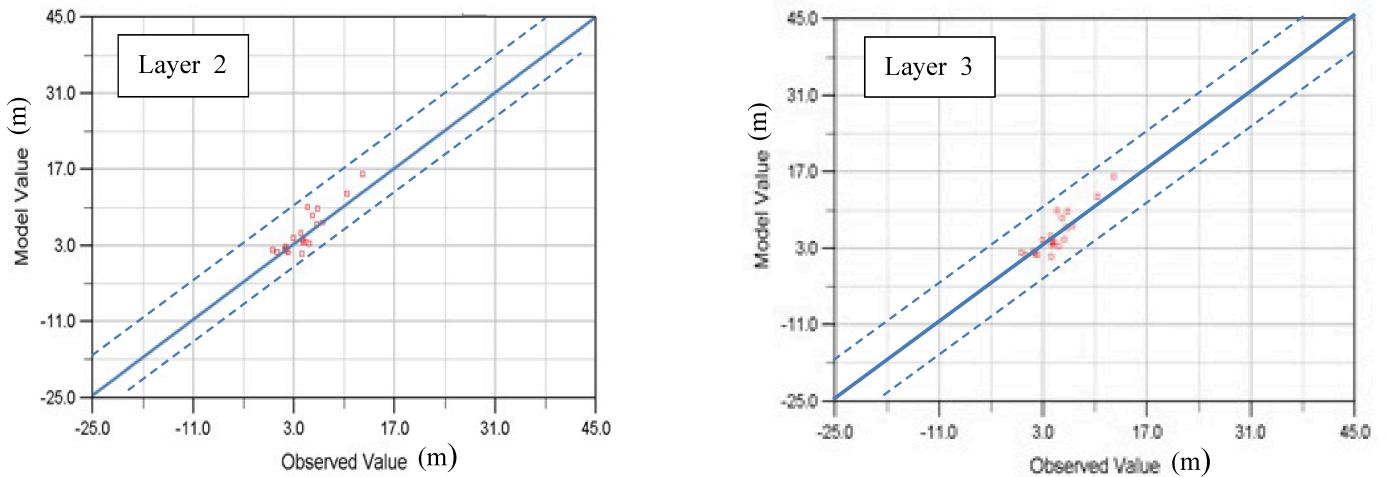


Figure 6. Scatterplot of steady-state calibrated and observed piezometric heads in the 2nd (left panel) and 3rd layer (right panel) with optimal fitting line and 95% confidence interval lines (dashed).

4 SCENARIO SIMULATIONS OF PLANNED WELL FIELD AND OF THE EFFECTS OF UNDERGROUND DAMS ON THE GROUNDWATER SITUATION

The primary purpose of the present study is the modeling of the effects of the planned well field in the study region on Koh Samui island on the future groundwater situation in the area, as well as the simulation of the possibly positive effects of the additional construction of two underground dams. To that avail, three modeling scenarios are investigated in this section, namely, (a) the present-day scenario, (b) a second scenario with the planned well-field, which is planned to pump 6,000 m³/day for the public water supply, and (c) a third scenario, which is based on that well field configuration, but includes, in addition, the two underground dams whose purpose is to impede groundwater flow towards the sea in the two mountain valleys (see Fig. 3).

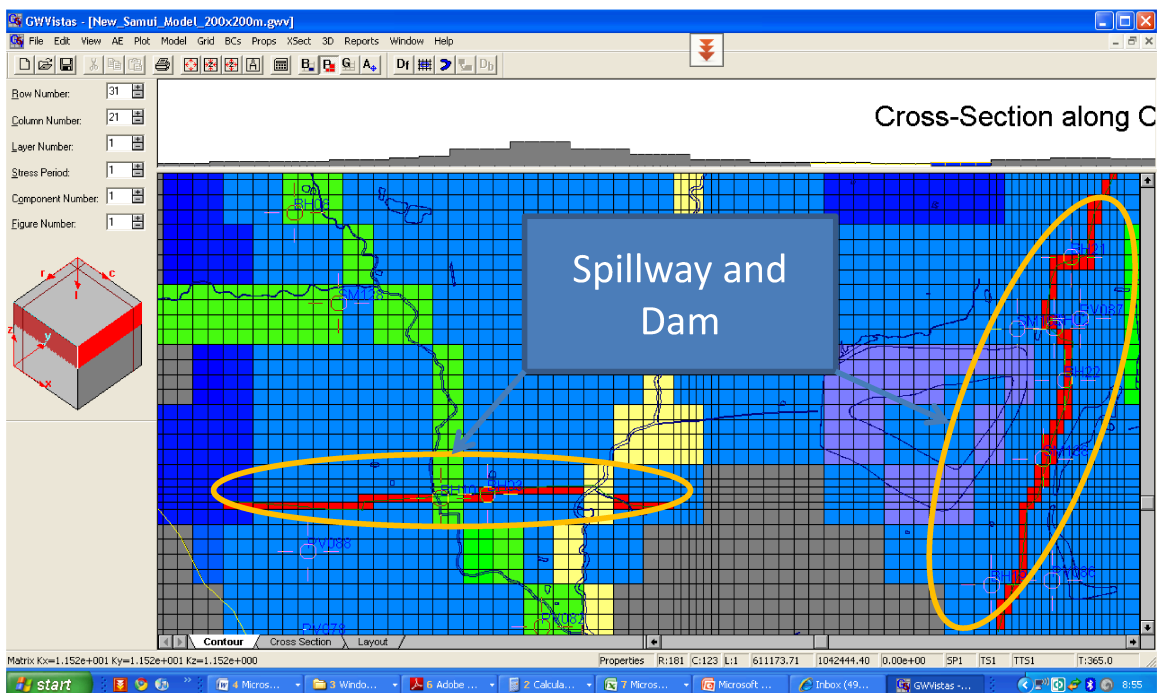


Figure 7. Visual MODFLOW[®] visualization of the locations of the two underground dams to be constructed to partly block groundwater flow toward the sea.

The actual construction of the dam will be realized by two, on a central impervious rock abutting low-permeability-, groundwater-flow-impeding walls with a width of 2m that cut through the three layers of the aquifer system, down to a maximum depth of about 50 m. Atop of the underground dam, which ends below the upper, unconfined aquifer layer, a vertical layer of high permeability will be set up, so that a

“spillway-like” overflow of the groundwater is enabled, in order to not disturb too much the subsurface ecology downstream. The locations of the two dams are outlined in Fig 7. In the model they are included in the form of two vertical low-conductivity curtain walls.

The three panels of Fig. 8 show the most salient results, i.e. the hydraulic heads, of the three scenario simulations. The first scenario-run (top panel) is based on the calibrated groundwater flow model of the previous section and serves as the baseline reference for the other two scenarios. From the top panel one may observe, as expected, that the simulated groundwater of the calibrated model flows unobstructed from the basin flanks toward the sea.

With the second scenario, i.e. forcing of the aquifer system by groundwater pumping of 6,000 m³/day, the middle panel of Fig. 8 unveils that a large cone of depression at the location of the well field has been established, wherefore the piezometric heads in the second 2nd layer are lowered down to its base.

The hydraulic head distribution of the third scenario plotted in the bottom panel of Fig. 8 provides clear evidence of the large benefit of the construction of the two underground dams. In fact, the piezometric heads are now maintained at levels above the bottom of the 2nd layer. This indicates that the underground dams are able to reduce the original drawdown due to the strong pumping, i.e. more groundwater is kept in the storage that is usable in the dry, high demand season.

Table 1. Average groundwater levels *WL* for scenarios without and with underground dams and additional storage *S* gained over the six month dry season with the underground dams.

Layer	WL.	WL.	S
	(m)	(m)	(10 ⁶ m ³)
	no dams	with dams	
1	14.25	13.75	*
2	16.75	17.19	0.12
3	9.65	9.70	0.05

* The first layer performs as a spillway and has thus no storage.

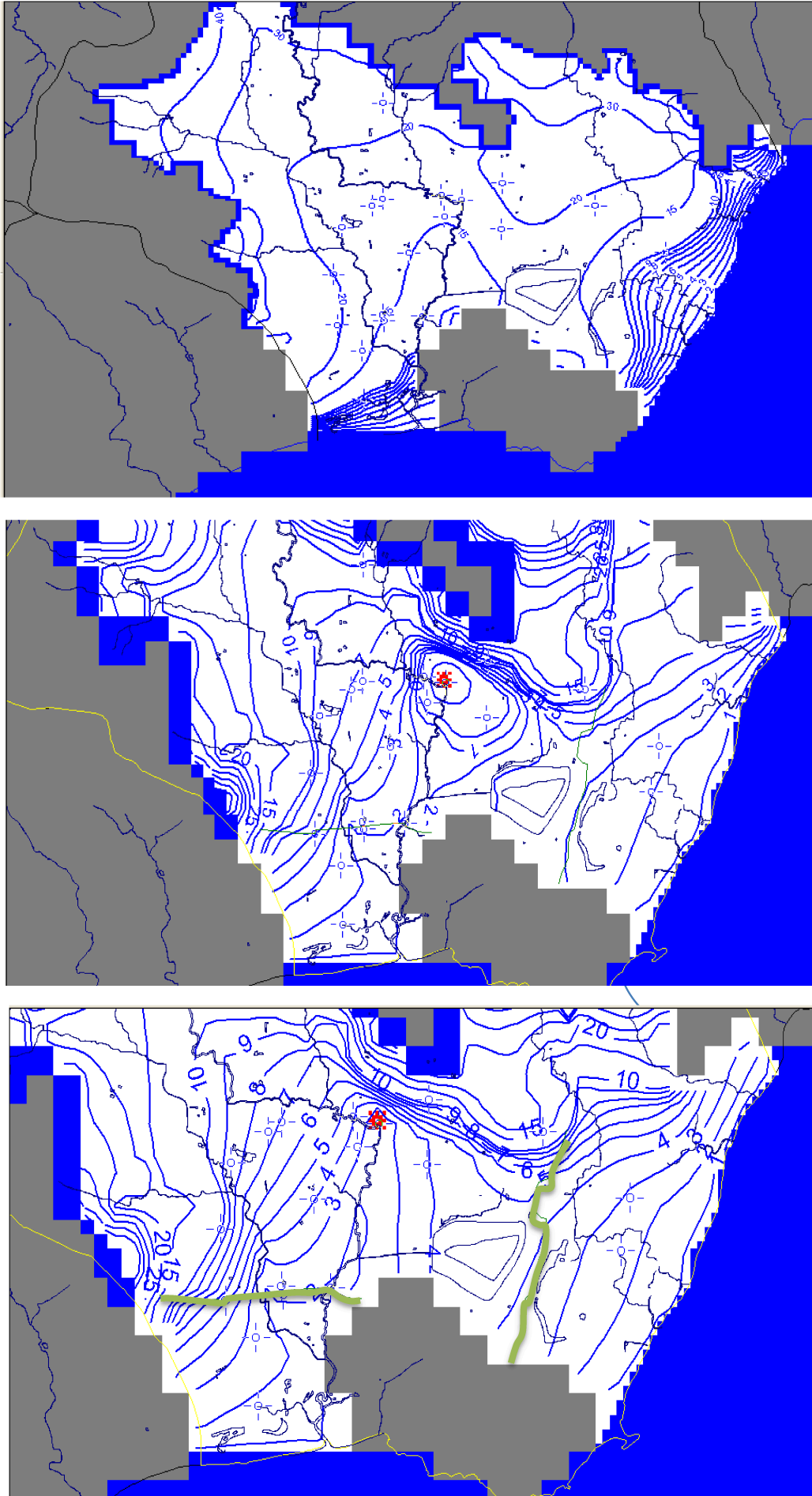


Figure 8. Piezometric heads in the 2nd layer for the first (present-day) (top), second (with well field, red point) (middle), and third (well field with underground dams, green lines) (bottom) scenario

This incremental storage due to the blocking of the groundwater flow toward the sea by the two underground dams has been quantified for the two confined aquifer layers (the upper unconfined layer acts a spillway and cannot, thus, store water). The results are listed, together with the average heads numerically obtained across the model domain, in Table 1. Thus one may notice that the additional six-month, dry-season (February to July) groundwater storage due to the two underground dams amounts to 170,000m³, which is a non-negligent quantity to be used for the public water supply, and this during a time period, when it is most urgently needed.

5 SUMMARY

The purpose of the study has been to investigate the feasibility of the implementation of two underground dams on Koh Samui island, in order to reduce the, nowadays, unobstructed flow of groundwater toward the sea which, in turn, would increase the groundwater storage in the aquifer system. This additional water might be used to serve for water demand in the dry season, when water consumers on the island, augmented by huge numbers of tourists, face critical water deficit situations.

The results of the 3D numerical groundwater modeling show indeed that the two proposed underground dams are able to mitigate the cone of depression due to the planned pumping of 6,000 m³/day, i.e. are able to raise the hydraulic heads in the well field during the (6-month) dry season by a significant amount. This leads to an increase of the groundwater storage which is computed as 170000 m³. This amount of water is then useable for extra dry-seasonal water supply on Koh Samui island.

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