CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

This chapter summarizes the results and findings obtained from steady-state groundwater flow simulation of the Bang Pakong river basin using MODFLOW program, and the model calibration based on automated parameter estimation scheme using PEST program. Parameter sensitivity analysis using both traditional method and a new approach based on parameter estimation scheme will also be discussed. Lastly, the result from uncertainty analysis of water budget using Monte Carlo analysis is presented. In short, the method used in this study involved four main steps: (1) developing a steady-state groundwater flow model; (2) calibrating the model based on automated parameter estimation scheme; (3) analyzing parameter sensitivity; and (4) analyzing model uncertainty using Monte Carlo technique.

First of all, a groundwater flow system of the Bang Pakong river basin is built using a finite-difference method based on United States Geological Survey's MODFLOW model. The numerical model consists of 161 rows, 121 columns, and 6 layers. A uniform horizontal grid size of 1000×1000 m^2 with variable thickness for all model layers was used. The major aquifers of this basin are unconsolidated to semi-consolidated aquifers of the Quaternary age. A set of algebraic nonlinear flow equations (especially for the unconfined aquifers) was solved using iterative solver which, in this case, is geometric multi-grid solver (GMG).

Prior to model calibration, the results of initial model execution indicate that hydraulic heads in the north-northeast and south-southeast regions were high and continuously decreased toward the center of the basin and groundwater discharged to the Gulf of Thailand (Figure 4-4). In some areas groundwater level dropped significantly below ground surface, especially in the coastal zone where groundwater abstraction was high due to agricultural, domestic, and industrial needs. The accuracy of initial model simulation was described by the goodness-of-fit indicative parameters: the root mean square (RMS) and normalized root-mean-square ($NRMS$) errors. These values were computed from 179 observation wells and they are 17.2 m. and 6.0 %, respectively. The model was then calibrated using automatic parameter estimation program namely PEST. The automatic calibration of 35 parameters was performed until the objective function was minimized; the error reductions in the values of heads compared between initial model executions vs. calibrated model using PEST is significant where RMS value is reduced from 17.2 m to 15.5 m and $NRMS$ value is reduced from 6.0 to 5.3 %. A subsequent parameter's sensitivity analysis allowed the assessment the relative importance of the model parameters. The result showed that the model outcome was sensitive to all parameter groups but was more sensitive to recharge rate and hydraulic conductivities.

The above results shows that the calibrated model still, at its best, produced some discrepancies between measured and calculated heads indicating that model could still produce result with error or, in other word, uncertainty. In order to quantify model's uncertainty, a stochastic method based on Monte Carlo technique was applied. In this method, multiple sets of parameter values were generated based on the optimized parameter values with a specified coefficient of variation. Multiple sets of steady-state simulations were then performed to evaluate the uncertainty of the model in response to changes in the values of all input parameters, with the random sampling method using log-normal and normal distribution. The number of model runs of 50, 100, 250, 500, 750, 1000, and 1,500 realizations were executed. After the simulations were completed, the results were statistically analyzed to obtain average and uncertainty range (i.e., 95% confidence interval) of the water budget and heads. The water budget, from the calibrated model was determined to be approximately 120.7 Mm^3/yr with an uncertainty of ±40.8 Mm^3/yr. The uncertainty in hydraulic head prediction was also presented in a map shown in Figure 4-14 where highly uncertain head measurements were delineated.

Although we cannot eradicate model uncertainty from any calibrated model, using stochastic method to quantify model uncertainty is possible and should provide valuable information for further decision-making on managing the basin. This study has illustrated how the advantage of uncertainty assessment will help to reduce the inconsistency and improve decision in groundwater resources management. In addition, this method can be especially useful for complex model and regional scale model that require a large amount of physical parameter fields and computational time.

5.2 Recommendations

- Since it is impossible to completely characterize aquifer's heterogeneity and spatial distribution of recharge rate, a groundwater flow model simulation should be capable of producing a range of possible outcomes which reflected the uncertainty in model parameter values (i.e., parameter uncertainty or model uncertainty) and displaying an acceptable level of confidence in flow model on report.

- Although the uncertainty assessment on steady-state condition was thoroughly investigated in this study, a more refined analysis of transient model simulation should provide year-by-year assessment for managing groundwater resource.

- Parameter sensitivity analysis showing the calibrated model was the most sensitive into recharge rate and hydraulic conductivity in a steady-state model. It would be more informative to further analyze the effect of storage coefficient of the transient model on uncertainty prediction.

- Stochastic modeling method (more precisely, Monte Carlo technique) is an important tool to predict uncertainty in model outcome based on the uncertainty in parameter values. It is recommended that the technique should routinely be used in all modeling work, especially the complex regional flow model, so that a statistically reliable bracket of groundwater potential or safe yield at some confidence level for decision could be obtained.

- It should be noted that the variation of hydraulic conductivity values obtained from pumping test analyses (249 wells) in some of the hydrogeologic units is considerably large. This wide range of K values is possible especially for an aerially extensive hydrogeologic unit. Pumping tests of the same hydrogeologic unit conducted at locations within highly fractured zone could result in a highly transmissive aquifer whereas the tests conducted within a non-fracture zone could, on the other hand, result in a small K aquifer. In setting up a flow model, a single value of hydraulic conductivity had to be selected to represent a hydrogeologic unit (i.e., heterogeneity was not considered within a hydrogeologic unit). This is a drawback of using *parameter zonation approach* in setting up a flow model because the model calibration could result in an unrealistically high value of hydraulic conductivity. To take into account these problems, more sophisticated techniques capable of handling aquifer heterogeneity should be used. These techniques are for examples Pilot Points and Multiple Zone Refining as described in Doherty (1994) and Harbaugh et al. (2000), respectively.