NUMERICAL INVESTIGATION OF COMBINED FLOOD MITIGATION AND GROUNDWATER RECHARGE IN THE CHAO PHRAYA RIVER BASIN

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Abstract

Gravitational recharge from flood retention reservoirs in the upper Chao Phraya river basin into the underlying Bangkok aquifers is numerically investigated by coupling the HEC-RAS river model to the MODFLOW groundwater model over the reservoir module RES1. As the Chao Phraya river basin often encounters flood inundation during the long Thai rainy season while, at the same time, the groundwater aquifer is increasingly being depleted from excessive pumping, the present study simultaneously serves two purposes. Thus the fundamental idea is to divert excess flood flow from the Chao Phraya river into the flood retention reservoirs to mitigate flooding in the lower parts of the basin. This retained water will gravitationally recharge into the Bangkok subsurface system, herewith increasing the amount of fresh groundwater. The feasibility of such a two-prong approach is investigated, whereby a flood retention reservoir in a seriously flood-inundated area in the basin, upstream of the Chao Phraya dam is selected. Using data from the heavy flood of 2006, the water stages in the retention reservoir are calculated for the flood-year 2006 with HEC-RAS. These serve as input in the reservoir module RES1 of the MODFLOW groundwater model, whereby groundwater recharge and heads are computed. The results disclose the positive potential of retention reservoirs for mitigating river flood while at the same time increasing recharge into the aquifers.

Key Words: Flood mitigation, Retention reservoirs, Groundwater recharge, HEC-RAS, MODFLOW

1. INTRODUCTION

Practically each year the lower Chao Phraya river basin including the Bangkok metropolitan area is encountering severe flood inundation problems; meanwhile the underlying Bangkok aquifer system has been heavily exploited over the last decades. As a consequence groundwater quantity and quality - through saltwater intrusion from upper marine layers - have significantly worsened over the years (Arlai, 2007; Koch and Arlai, 2007). Presently Thai water authorities attempt to tackle both of these problems through a variety of sustainable solution approaches. One – based on the invaluable wisdom of "His Majesty the King" Bhumiphol of Thailand - consists in establishing several detention or recharge reservoirs along the Chao Phraya river. Such a solution would practically kill two birds with one stone, as a detention/recharge reservoir would not only retain a huge amount of diverted flood water from the river - decreasing the flood peak during the rainy season there- but, at the same time, would also act as a recharge source to the underlying Bangkok aquifers system - alleviating the aforementioned groundwater problems there.

However, before such an intriguing suggestion should be realized it must undergo a careful hydrological investigation. This is the objective of the present paper and it will be endeavored by a numerical evaluation of the surface recharge of a retention reservoir next to the Chao Phraya River into the Bangkok aquifers system. To that avail the surface water (river) model HEC-RAS (http://www.hec.usace.army.mil/software/hec-ras/) will be coupled to the MODFLOW-96-groundwater flow model (McDonald and Harbaugh, 1988) by means of the RES1-reservoir module (Fenske et al., 1996), an approach which, to the authors knowledge, has not yet been undertaken.

2. STUDY AREA

The Bangkok aquifer system is located underneath the lower Chao Phraya River Basin which is bordered in the east, north and west by hills and mountains and in the south by the Gulf of Thailand (Fig. 1). The multi-aquifer system is comprised of a topmost soft/stiff clay layer and eight complex water bearing layers under Bangkok and neighboring provinces (cf. Arlai, 2007; and Arlai and Koch, 2007, for details). The prime recharges into the groundwater basin occur at the basin flanks, where the 2nd to 4th aquifer layer are outcropping (Kokusai Kogyo Co., Ltd., 1995).

The study site of a possible flood retention/recharge reservoir used in the present investigation is located at the upstream of the main diversion dam of the Chao Phraya river—the Chao Phraya Dam. This location appears to be the most appropriate one for the purpose of the study, as here, one hand, flood water can easily be diverted towards the retention reservoir while, on the other hand, the low-permeable marine clay layers which are prevalent throughout the lower portion of the Chao Phraya river basin do not pose anymore much of a barrier to surficial groundwater water recharge here.

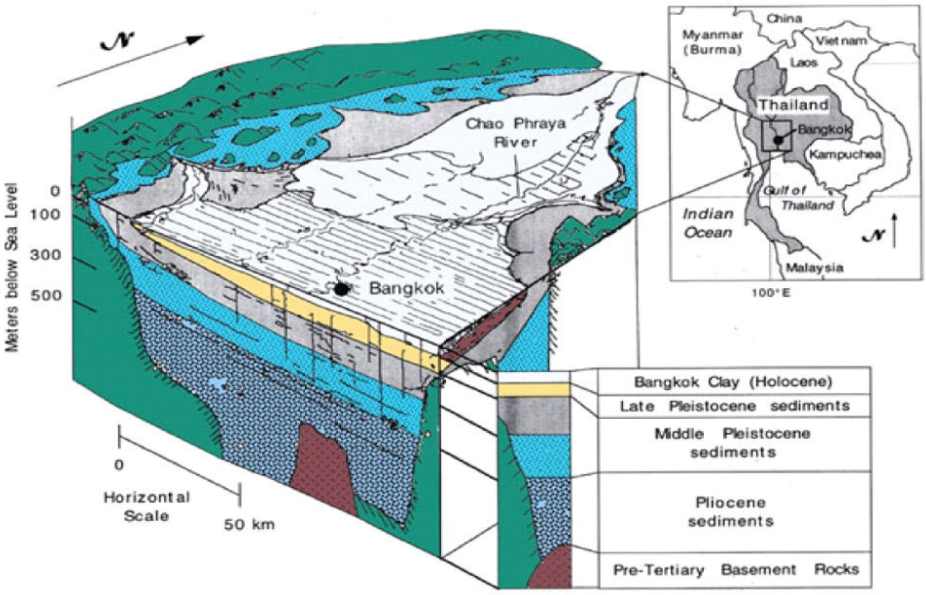

Fig 1. 3D map of the lower Chao Phraya river basin

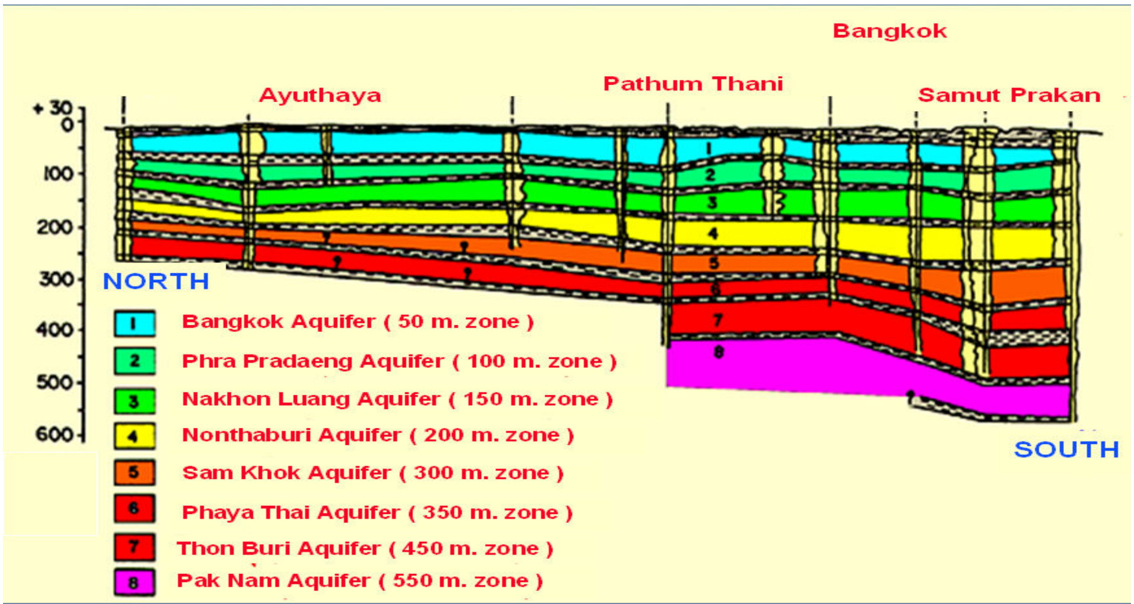

Fig. 2. Hydro-geological profile of the Bangkok aquifer system

3. MODEL IMPLEMENTATION

3.1 HEC-RAS model for the Chao-Phraya river system

For the purpose of the present study two hydrological models, the HEC-RAS-river model and the MODFLOW-96-groundwater model are coupled to each other over the MODFLOW reservoir module RES1. While there have been several investigations in recent years to couple HEC-RAS to MODFLOW in the vicinity of rivers and/or drainage canals, though in the other direction (groundwater to surface water) (cf. Rodriguez et al., 2008), no such approach for the application of the reservoir recharge has been endeavored up-to-date.

HEC-RAS's required geometrical input data consists of GIS- coordinates of the Chao Phraya river lines, -cross sections, and of the various hydraulic structures along the river course. This data has been retrieved from hard-copy maps or in taken in digital form from the Royal Irrigation- and/or the Marine Department. The data is further processed using the ArcGIS environment as implemented in HEC-GeoRAS (http://www.hec.usace.army.mil/software/hec-ras/hec-georas.html). Other input data are the Manning roughness-coefficient "n", as well as gate coefficients and contraction-/expansion coefficients for the various hydraulic structures along the modelled river course. However, as these parameters are usually not well-known, they are adjusted during the calibration process itself.

The HEC-RAS model has been calibrated in steady and unsteady mode using stage and flow data of the big flood event of 2006 over a seven-month period recorded at different river monitoring stations, namely, Manorom, Makham Tao-Utong, Maharaj, C.3, C.7A and C.4 stations (Fig. 3). As an example, Fig. 4 shows results of the calibration for station C7A which is the last one upstream of Bangkok. One can unveil a rather good fit of the computed to the observed water levels in the Chao Phraya River.

For the surface-water modeling of the flood retention/recharge reservoir - which is to be linked later with the groundwater system through the reservoir module of MODFLOW - the storage area module of HEC-RAS is employed. Physically, the river is connected with the reservoir through a weir at the river bank and a delivering open canal. The purpose of the weir is also to perform as a sediment trap for river water before entering the canal. For the location of the flood retention reservoir an area which is often inundated during the rainy season has been chosen (Fig.3).

Fig. 3 HEC-RAS model of the lower Chao Phraya river basin with calibration stations and the flood retention/recharge reservoir. The smaller inlet represents a zoomed-in map of a typical river reach that has been used for the preparation of the ArcGis maps and the input data.

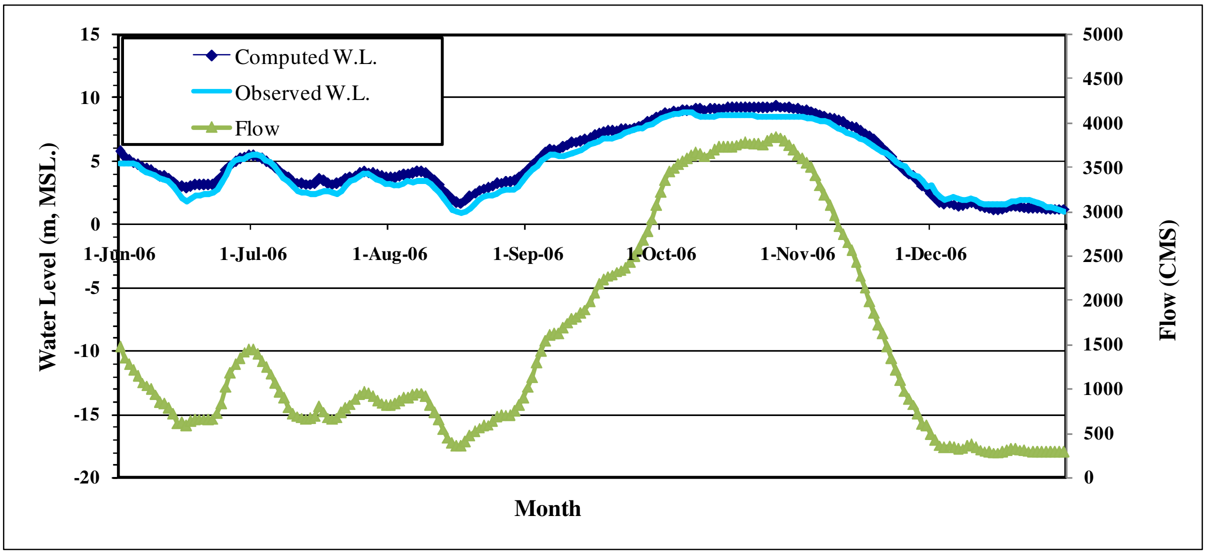

Fig. 4 **HEC-RAS calibration of the Chao Phraya river flood of 2006**

3.2 MODFLOW- model of the Bangkok aquifer system

The groundwater flow model for the Bangkok aquifer system is implemented by means of the quasi 3D finite-difference model MODFLOW-96, an update of MODFLOW (McDonald and Harbaugh, 1988). In accordance with the hydro-geological conceptual model of the Bangkok multi-layered aquifer system as shown in Fig. 2, 9 aquifer layers are simulated, whereby the topmost clay layer is treated as an unconfined aquifer and the 8 lower ones as confined ones. The aquifer model is divided horizontally into 55 rows and 52 columns, with grid sizes varying from 2*2 km^2 to 16*16 km^2. following the MODFLOW modeling approach of Kokusai Kogyo (1995). The groundwater flow model is calibrated in steady state (1999) and transient (1999 – 2003) mode (cf. Arlai, 2007; and Koch and Arlai, 2007, for details). Then the reservoir module RES-1 embedded in MODFLOW-96 is activated to link the groundwater flow model to the HEC-RAS surface-water model.

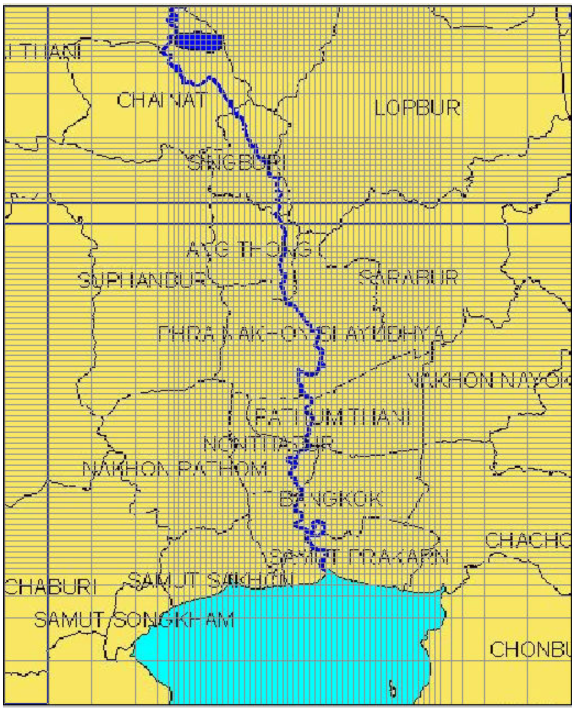

Fig. 5. Finite-difference grid used in the MODFLOW-96 groundwater model. The blue area denotes the location of the flood/recharge reservoir as implemented in the RES1-module.

3.3 Coupling between surface water- and groundwater flow model

The surface– to groundwater coupling between HEC-RAS and MODFLOW-96 through the storage area and the reservoir module, respectively, is a one-way explicit link, i.e. it is assumed that there is no direct feedback of the groundwater flow onto the flood water in the retention reservoir. This simplified approach is reasonable, given the different time-scales of surface- and groundwater flow. Thus, the impact of flood water on the groundwater acts on a much smaller time-scale (days to weeks) than the feedback of the groundwater system on the surface water (months to years). With these considerations in mind, the coupled HEC-RAS- MODFLOW-96 model works as follows: (1) The transient water stage in the flood reservoir is calculated with the HEC-RAS storage area module, (2) these water levels are imported as boundary conditions into the reservoir module of MODFLOW-96 and the ensuing groundwater recharge is computed. To accommodate the aforementioned different time-scales of the two flow-systems, a common time-step of one day is used in the simulations.

4. RESULTS

In account of the objectives of the present study, the results of the numerical simulations are to be evaluated with respect to (1) the mitigation of flooding in the Chao Phraya river basin, and (2) the recharge of flood water into the groundwater system.

4.1 Mitigation of flooding

The large Chao Phraya river basin flood in 2006 is modeled with two main scenarios, namely, (1) without the presence of a retention reservoir, and (2) with the implementation of such a reservoir. Fig. 6 illustrates that the peak water levels along the Chao Phraya river are consistently lower for scenario (2) than for scenario (1). These results clearly indicate that a retention reservoir is indeed able to reduce the flood levels in the Chao Phraya River, reducing the risk of overbank flow at many locations along the river, especially, downstream of the Chao Phraya dam, upstream of Bangkok.

4.2 Recharge into the groundwater system

Fig. 7 shows the variation of the water levels in the retention/recharge reservoir as computed with HEC-RAS and the storage area module as well as both the daily and the cumulative recharge computed with MODFLOW-96 / RES1. Comparing the monthly evolution of these variables with that of the flood in the Chao Phraya river itself (Fig. 4), one notes that the water stage in the reservoir responds more or less immediately to that in the river and reaches its peak in November, i.e. at the same time when the river stage has also attained its maximum.

One the other hand, the recharge curves of Fig. 7 indicate a certain delay of the groundwater recharge to the flood stage. Thus, a noticeable amount of recharge, particularly, of the cumulative volume recharged emerges only in November, i.e. two months after the beginning of the flood event. Obviously some time is needed before the surface water has percolated down into the aquifer system. The total (cumulative) amount of recharge is about $5.7\text{x}10^5$ m^3 for the whole flood season which, in Thailand, ends at the end of the calendar year. It goes without saying that, because of the time-delay mentioned, recharge will certainly continue beyond this date. Further computations are required to evaluate this additional amount. However, as it is to be expected that this extra recharge will be much less than the amount calculated above, the overall conclusion to be drawn from these results will not be affected much. Thus, considering that the total daily pumping from this aquifer system with a total area of $200\text{x}150$ km^2 is around $1.3\text{x}10^6$ m^3/day, the recharge volume calculated above appears to be negligible to restore groundwater quantity in a measurable way. Obviously more retention/recharge reservoirs are needed to get a significant impact on groundwater recharge in the study region.

5. SUMMARY

Gravitational recharge from flood retention reservoirs in the Chao Phraya river basin into the underlying Bangkok aquifers is numerically investigated by coupling the HEC-RAS river model to the MODFLOW groundwater model over the reservoir module RES1. Our approach goes beyond that of many other studies of groundwater recharge from leaking ponds (cf. D'Oria et al., 2008) which rely on the simulation of the groundwater compartment alone.

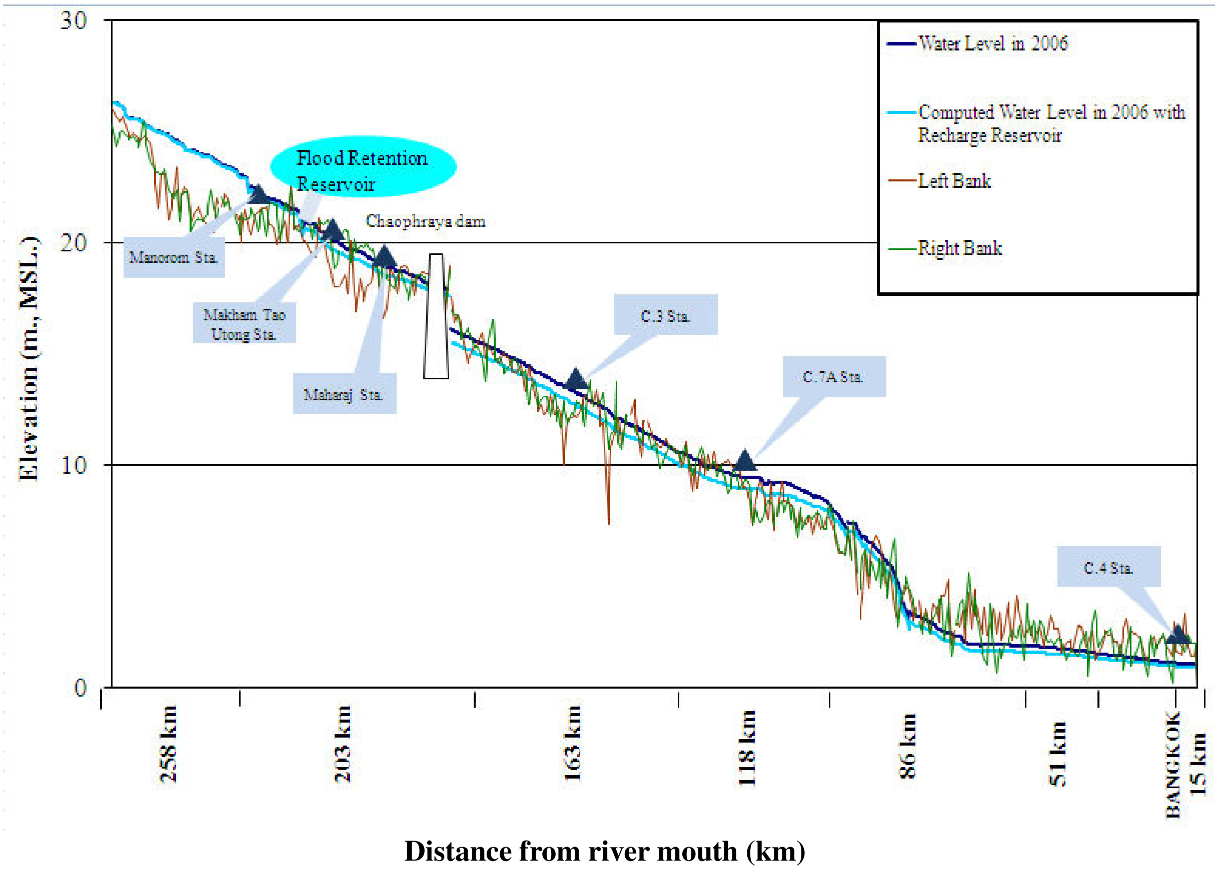

Fig. 6. Flood level profiles along the Chao Phraya river for scenario (1) - dark blue line and scenario (2) (with retention reservoir) - blue line (see text, for explanations)

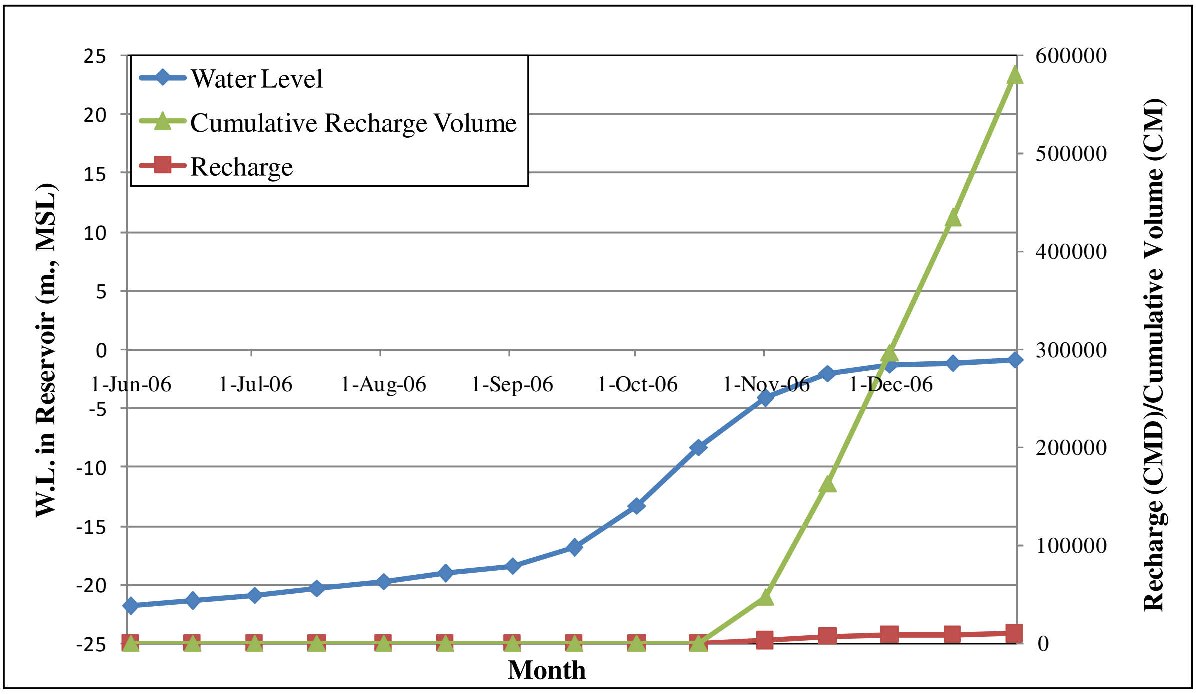

Fig. 7. Water levels, daily recharge and cumulative recharge of the retention reservoir.

In the present study a flood retention/recharge reservoir is selected from a seriously flood-inundated area in the basin, up-stream of the Chao Phraya dam. The river model is calibrated on the 2006-flood period which begins in June and ends in December. The results of the coupled model unveil that the retention reservoir can positively reduce flood water levels in the Chao Phraya river, since flood water starts to significantly flow from the river into the reservoir in early October. As the water table here rises, groundwater recharge starts to increase as well, though with a month-long time delay. By the end of the 2006-calendar flood year (December, 31), the groundwater-modeled, cumulated recharge amounts to around half million cubic meters. Compared with the overall groundwater pumping in the Bangkok aquifer system, such a recharge volume appears not to be significant for alleviating the imminent groundwater shortage there. Clearly more and larger water retention reservoirs are needed to that avail and this is being investigated at the present time the authors.

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REFERENCES

[1] Arlai, P. 2007: Numerical Modeling of possible Saltwater Intrusion Mechanisms in the Multiple-Layer Coastal Aquifer System of the Gulf of Thailand, Dr.-Ing. Dissertation, School of Civil Engineering, University of Kassel, Germany.

[2] Arlai, P., and M. Koch**,** 2007: Numerical Investigation of the original Sources of saline Pollution and efficient Remediation Scenarios in the Bangkok multilayer-Aquifer System , In: Proceedings of 12th National Convention on Civil Engineering, Phitsanulok, Thailand, May 2-4, 2007

[3]D'Oria, M., M. Tanda, and A. Zanini, 2008: Flood water storage as a resource for agriculture and groundwater recharge: the empting of artificial leaking ponds, American Geophysical Union, Fall Meeting 2008, abstract #H13G-1006.

[4] Fenske, J.P., S.A. Leake, and D.E. Prudic, 1996: Documentation of a Computer Program (RES1) to Simulate Leakage from Reservoirs Using the Modular Finite- Difference Ground-Water Flow Model (MODFLOW), U.S. Geological Survey Open-File Report 96-364.

[5] Koch, M. and P. Arlai, 2007: Deterministic and stochastic Modeling of Groundwater Flow and Solute Transport in the heavily-stressed Bangkok coastal Aquifer, Thailand, and Investigation of optimal Management Strategies for possible Aquifer Restoration, IAH 2007, Groundwater and Ecosystems, Lisbon 2007, Lisbon, Portugal, September 17-21, 2007.

[6]Kokusai Kogyo Co., Ltd., 1995: The Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and its Vicinity, Final and Main Report, which was funded by JICA and presented to Department of Mineral Resources, Department of Industry and Public Works Department, Ministry of Interior, Thailand.

[7]McDonald, M.G. and A.W. Harbaugh, 1988: A modular three dimensional finite different ground-water flow model, Water-Resources Investigations Report 83-875, USGS.

[8]Rodriguez, L.B., P.A. Cello, C.A. Vionnet and D. Goodrich, 2008: Fully conservative coupling of HEC-RAS with MODFLOW to simulate stream–aquifer interactions in a drainage basin, J. Hydrology, 353, 129-142.