A projection of groundwater resources in the Upper Chao Phraya River basin in Thailand

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Abstract:

Depletion of groundwater is expected due to climate change. This study describes a catchment-scale study on projected groundwater recharge and storage in the Upper Chao Phraya River basin under changing climate scenarios. The period from 2026 to 2040 was assessed using climate projection results from global climate models (GCMs). Three GCMs, namely MIROC-ESM-CHEM (MIROC), HadGEM2-ES (HadGEM), and GFDL-ESM2M (GFDL), were used along with four greenhouse gas emission scenarios, namely RCP2.6, RCP4.5, RCP6.0, and RCP8.5, as the climate change conditions. The projected changes in groundwater recharge and storage were quantified as percent differences from the simulated recharge and storage for the reference period (1986–2000). A significant trend of decreasing mean monthly rainfall from April to June was detected for the HadGEM and the GFDL models. This change in rainfall pattern was projected to reduce the mean annual groundwater recharge (storage) by −12.9% (−1.46 km³), −9.7% (−1.35 km³), −13.9% (−1.49 km³), and −10.7% (−1.38 km³) for the RCP 2.6, 4.5, 6.0, and 8.5 scenarios, respectively. Based on the results of the relative change in groundwater storage, we expect that groundwater resources will be affected by climate change and that both groundwater recharge and storage will be reduced.

KEYWORDS climate change; groundwater recharge; groundwater storage; Upper Chao Phraya River basin

INTRODUCTION

Depletion of groundwater is expected due to climate change. Gleeson et al. (2012) showed that approximately 1.7 billion people around the world live in areas where groundwater resources are under threat by over exploitation of groundwater. Döll (2009) projected climate change impacts on groundwater resources using two climate models (ECHAM4/OPYC3 and HadCM3) under the A2 and B2 scenarios and found that by 2050, more than 10% of the renewable groundwater resources could be decreased for approximately one fifth of the global land area, which would affect approximately 2.4 billion people. Projected future temperature increases and rainfall variability are expected to reduce groundwater resources as a first response to climate change. However, the relative rate of change (e.g., groundwater recharge) and how it will relate to groundwater storage are not completely known (Seibek and Allen, 2006). The relationship between groundwater and climate change remain a topic of keen interest to researchers. From 1990 to 2010, there were approximately 198 peer-reviewed publications that focused directly on climate change and groundwater, but the potential impacts of climate change on groundwater, and the future of groundwater, in the context of global and regional climate change remain largely unknown (Toews and Allen, 2009; Green et al., 2011; Kurylyk and MacQuarrie, 2013).

In the northern part of Thailand where the Upper Chao Phraya River basin (UCP, Supplement Figure S1a) is located, the Department of Groundwater Resources (2011a) conducted a study of conjunctive water use and enhanced use of groundwater to meet household water demands during dry periods. The results of the study showed that some areas, e.g., the Lower Yom and Nan River basins and the Chiang Mai–Lamphun, Lampang, and Phrae areas (Supplement Figure S1b), had the potential to develop irrigation areas using groundwater. Groundwater withdrawal to meet the demand for water for rice growing is becoming increasingly popular. It is crucial that groundwater be used in a sustainable manner and that the effect of climate change on groundwater resources be projected. Koontanakulvong et al. (2010) studied projections of irrigation water use by the Plaichumpol Irrigation Project (Supplement Figure S1b) in the near future (2015–2039) and more distant future (2075–2099) using MRI GCM data. The mean annual rainfall is projected to decrease by approximately 0.5% in the near future between 2015 and 2039 but increase by approximately 8.9% between 2075 and 2099, compared to the baseline period (1982–2005). Between 1994 and 2006, approximately 66 to 186 million cubic meters of groundwater per year was withdrawn to grow rice because not enough surface water was available. For the UCP as a whole, it is estimated that approximately 1,508 million cubic meters of groundwater per year can be withdrawn from groundwater storage without groundwater depletion (Ramnarong and Wongsawat, 1999).

Molle (2002) and the Department of Water Resources (2007) showed that agricultural water use is increasing, mainly as a result of expansion of irrigated areas especially during dry periods. The ratio of supply to demand becomes critical for almost 6 months of the year (during the dry season). The
Office of Agricultural Economics (2012) reported that the area planted with rice in the northern region during the dry season increased by 33.2% from 2010 (9,147 km$^2$) to 2012 (12,185 km$^2$). This causes more water consumption in the region. Groundwater is an available option to cope with surface water shortage that is now accelerated by climate change. Evaluation of the future of groundwater in the context of climate change will benefit future groundwater management in the region.

Numerical modeling is a quick and useful approach to assess past and future groundwater resources in response to climate change. In Thailand groundwater resources have not been widely studied, especially regarding climate change effects. For example, the interactions among climatology, groundwater recharge and storage changes are largely unknown. This study was conducted to assess the potential effects of climate change on groundwater recharge and storage in the UCP. Three GCMs (i.e., MIROC, HadGEM, and GFDL), which are earth system models (ESMs) that include consideration of biogeochemical processes, were used for this purpose. These models were compared and results cross-checked as part of the Inter-Sectoral Impact Model Intercomparison Project (http://www.isi-mip.org/) (Hanasaki et al., 2013). Different GCMs were selected to reflect the uncertainties in GCMs. The study period of 2026–2040 was selected because we considered it reasonable to assume that the land cover will not be altered to a large extent during this period.

The two main objectives of the study were (1) to determine the ranges of temporal and spatial variability of groundwater recharge and storage corresponding to various future climate scenarios, which have not been explicitly studied for the UCP; and (2) to estimate the relative changes in recharge rates and groundwater storage.

### STUDY AREA

The UCP is located in the northern part of Thailand and covers approximately 109,973 km$^2$, or 22% of the country's area (Department of Water Resources, 2007). The basin can be divided into four river sub-basins, the Ping, Wang, Yom, and Nan River basins, based on topography (Supplement Figure S1b). Two large reservoirs lie on the Ping and Nan Rivers and hold a total approximately of 23 billion cubic meters of water for use in managing water resources for both the Upper and Lower Chao Phraya River basins.

The climate of the UCP actually has three seasons, but for simplicity, we considered only two: a wet season (May to October) and a dry season (November to April). The first prevailing tropical rainfalls from the South China Sea dominate the weather in the basin from May to the end of June. The second monsoon usually takes place between August and October. The spatial average annual rainfall is approximately 990 mm (1986–2000). Almost 88% of this rainfall occurs during the wet season. According to the available land use classification data, approximately 60.0% of the area of the UPC is forested, 35.6% is used for agricultural purposes, and 4.4% is classified as water bodies, urban areas, and other land uses (Department of Water Resources, 2007).

### METHODOLOGY AND DATA

#### Methodology

This study was conducted using numerical models, as illustrated in Figure 1. A regionalized version of the global water resources model, called H08, with a 5 min × 5 min spatial resolution (Hanasaki and Mateo, 2012), was used to simulate the surface hydrological variables (e.g., surface runoff, river discharge, evaporation, and air temperature) that serve as inputs for other models. The original H08 model consists of six modules (Hanasaki et al., 2008). However, for this study, only three of these modules were used: the land surface module (LSM), the river routing module, and the reservoir operation module. The LSM is governed by the soil water balance and energy balance equations (Manabe, 1969; Robock et al., 1995). A 0.5 m$^3$ s$^{-1}$ flow velocity was fixed in the river routing module (Oki and Sud, 1998), and a mean seasonal release was applied to the downstream reservoir in the reservoir operation module (Hanasaki and Mateo, 2012). The other three modules in the H08 model were not used because their roles are limited for this basin, compared to the three modules mentioned.

A shifting and scaling technique (e.g., Alcamo et al., 2007; Hanasaki et al., 2013) was applied to correct the bias of the GCMs’ outputs for rainfall, air temperature, and longwave downward radiation. This technique takes a time series of current climate data and adds or multiplies meteorological elements affected by climate change to create meteorological data for future climates for a given climate change scenario. Longwave downward radiation was included in the correction process because this term exhibited an increasing trend for all of the GCMs (Hanasaki et al., 2013).

A spatial finite difference grid with a 5 min × 5 min spatial resolution and a technique for solving a tri-diagonal matrix by Gaussian elimination for columns and rows (Prickett and Lonnquist, 1971) were used to solve the conservation groundwater flow equation shown as in Equation (1):

$$ \frac{Q}{Q_{r}} = R - E - R_{0} - R_{o} = \text{Rainfall} - \text{Evaporation} - \text{Runoff} - \text{River discharge} $$

Figure 1. Schematic diagram of model and data
\[
\frac{\partial}{\partial x}(T_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_y \frac{\partial h}{\partial y}) = \frac{\partial}{\partial t}(\frac{\partial h}{\partial t}) + Q_i + Q_n
\]

where \(T_x, T_y, h, S, Q_i\) and \(Q_n\) are the transmissivity (m² day⁻¹) in the \(x\) and \(y\) directions, respectively, the groundwater level (m), the storage coefficient, and the groundwater recharge and discharge rates (m day⁻¹) from rainfall over a land area (see Supplement Text S1), and river-induced infiltration (m day⁻¹), respectively. In this study, for the sake of simplicity, we assumed that the transmissivity of the aquifer is the same in the \(x\) and \(y\) directions. Setting groundwater flow model boundaries and simplification of an aquifer layer to calculate groundwater storage are presented in Supplement Text S2.

The projected changes in the values of the hydrological parameters over the study period (2026–2040) were quantified in terms of percentage differences from their simulated values for the reference period (1986–2000). A spatial average value of the projected results for each scenario was applied to take into account the projected ranges of the different GCMs in order to compare their changes (e.g., Jackson et al., 2011).

**Data**

The input climate data (i.e., rainfall, air surface temperature, wind speed, specific humidity, and longwave and shortwave downward surface radiations) were provided by Kotsuki et al. (2010), hereinafter referred to as the K10 data. These data have a spatial resolution of a 5 min × 5 min. The projections of the three GCMs that were considered in the World Climate Research Program’s Coupled Model Inter-Comparison Project (CMIP5) for four greenhouse gas emission scenarios termed Representative Concentration Pathways (van Vuuren et al., 2011) were used in this study. These four scenarios reflected one low level of emissions (RCP2.6), two intermediate levels of emissions (RCP4.5 and RCP6.0), and one high level of emissions (RCP8.5) (van Vuuren et al., 2011). The transmissivity (350 m² day⁻¹), the storage coefficient (2.5 × 10⁻³), and the spatial distribution of the effective porosity of soil over the target region, which depend on the range of soil textures encountered in the UCP (0.07–0.22), were obtained from Department of Groundwater Resources (2011b, 2011c, and 2012), Streambed properties, i.e., the thickness (0.30 m) and hydraulic conductivity (5 × 10⁻² m day⁻¹), were averaged from streambed data collected in the field by Koontanakulvong et al. (2010) and Department of Groundwater Resources (2011c). Observed mean groundwater levels in the Lower Yom and Nan River basins were obtained from the Department of Public Works and Town & Country Planning in Thailand and were used to validate the groundwater flow model.

**RESULTS AND DISCUSSION**

The following section is divided into seven sub-sections. The first two sub-sections (validation of river discharge at C.2 basin outlet station (Supplement Text 3) and spatial mean groundwater level and spatial distribution of groundwater basins) illustrate the validation of our models. Then, five sub-sections are presented, including: an overall discussion regarding the limitations of the projected results, the climatology, groundwater recharge, storage, and comparison of spatial mean groundwater levels in the wet and dry months (Supplement Text 4).

**Validation of the spatial mean groundwater level and the spatial distribution of groundwater basins**

The groundwater recharge and aquifer properties were input into the groundwater flow model, and the temporal and spatial variations in groundwater levels and groundwater storage were calculated. There was a limitation in groundwater level observations for the UCP as a whole. However, we obtained spatial mean groundwater level data for the Lower Yom and Nan River basins from the Department of Public Works and Town & Country Planning (Supplement Figure S4). Those data yielded an \(R^2\) of 0.68 between the two data sets (simulation and observation; Figure 2). This error resulted from the model using the average ground surface elevation and only one value of the groundwater level for each grid area of a 5 min × 5 min spatial resolution, which was a large grid area (98.5 km²). The effect of the area’s topographical characteristics on groundwater levels are not well reproduced at this spatial resolution, which is a limitation of the model. However, the model performance is considered useful and acceptable for the purpose of assessing groundwater resources at the basin-scale.

According to the hydro-geological site investigation by the Department of Groundwater Resources (2011a, 2011b, and 2012), there were five groundwater basins (black dot line in Supplement Figure S5) distributed over the entire UCP: the Lower Yom and Nan, Chiang Mai-Lamphun, Lampang, Phrae, and Nan. Comparison of the simulated mean groundwater levels during the reference period within the five groundwater basins (overlays as shown in Supplement Figure S5) showed that, in the shallow groundwater basins (dark red shading), the model mimics the site investigation data well. This suggests that the model was capable of reproducing the spatial distribution of groundwater basins in the UCP.

**Projection of climate variables**

Supplement Table S1 shows four main hydrological variables (rainfall, surface runoff, evaporation, and air temperature) for both the reference period (1986–2000) and
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the projection period (2026–2040) obtained with the three GCMs, for a total of four scenarios (in total twelve experiments). The model provides general trends in hydrological variables from the reference period to the projection period.

After applying bias correction to the GCM data, the MIROC model projects that mean annual rainfall will increase by 0.1–6.1% between the reference and projection periods, but the HadGEM and GFDL models project decreases of 6.5–15% and 2.2–8.5%, respectively. Averages of the projections from the three GCMs for each climate change scenario indicate decreases in the mean annual rainfall of 50, 33, 56, and 41 mm for the RCP 2.6, 4.5, 6.0, and 8.5 scenarios, respectively, relative to the reference period (1986–2000). We detected a significant decreasing trend in the mean monthly rainfall (outside the one-standard-deviation range) for the months of April through June, and even stronger decreasing trends for the HadGEM model (18–28%). Increases in the mean annual temperature in the range of 1.3–1.8°C in the UCP were projected by the GCMs for the various scenarios. The highest temperatures were projected by all GCMs for the RCP8.5 scenario. The spatial distribution of air temperatures in April (the hottest month) over the UCP was projected to increase by 2.5 to 3.8°C.

According to the LSM simulation, approximately 82.0% of the mean annual rainfall was lost through the evaporation process during the period 1986–2000. Under the future projections, the three GCMs yielded averages of approximately 83.3%, 83.1%, 83.6%, and 83.1% of the mean annual future rainfall lost to evaporation for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, respectively. These results indicate that over the projection period, the projected increases in the surface air temperature are not notably different among the four scenarios. The mean annual surface runoff values for the projection period were −2.7 to −31.6% or 4.9–56.4 mm lower than for the reference period for all scenarios according to the HadGEM and GFDL models, and for the RCP6.0 scenario according to the MIROC model, or, in other words, for 9 of 12 experiments.

Projection of groundwater recharge

Figure 4 shows accumulated mean monthly groundwater recharge for both the reference and projection periods. Nearly 100% of the recharge occurs between May and October. The maximum groundwater recharge month for both the reference and projected periods is in August, which is also the month with the greatest rainfall. According to the historical simulation, there was approximately 93 mm (approximately 9.4% of the mean annual rainfall) in mean annual groundwater recharge average over the UCP. The amount of calculated groundwater recharge is consistent with other studies of the UCP, such as Ramnarong and Wongsawat, 1999; Döll, 2009; and Koontanakulvong et al., 2010. The future projections showed a large range in the mean annual groundwater recharge, from 63 mm (a −32.3% decrease) to 98 mm (a +5.4% increase). This range is consistent with the findings of Döll (2009), who obtained projected changes in groundwater recharge in Thailand from −30% (decrease) to +10% (increase) by 2050, using the ECHAM4 and HadCM3 models under the A2 and B2 scenarios. In addition, we note that the projections varied predominantly by GCM rather than by scenario. This highlights that groundwater recharge projections are sensitive to the GCM used (e.g., Döll, 2009; Kurylyk and MacQuarrie, 2013).

Supplement Figure S6 shows the future projections of the mean annual spatial groundwater recharge for the twelve experiments by three GCMs forced by four scenarios. To assess the changing trend, we compared the projected results with the historical simulation. With the MIROC model, increases in the mean annual groundwater recharge of +3.2 to +5.4% were projected for all scenarios except the RCP6.0 scenario. On the other hand, decreases of −7.5 to −32.3% were projected with the HadGEM and GFDL models. The maximum projected decrease in the mean annual groundwater recharge was −32.3%, obtained with the HadGEM model for the RCP6.0 scenario, and is attributable to the extreme decrease in projected rainfall. However, it

![Figure 3. Upper panel: mean monthly rainfall for the reference period (1986–2000) and projection period (2026–2040) for the twelve scenarios analyzed with the three GCMs. The light blue shaded area represents a band of one standard deviation. Lower panel: scenario analysis used to assess the projected trends](image-url)

![Figure 4. Accumulated mean monthly groundwater recharge](image-url)
should be noted that the decreasing rate of groundwater recharge is evidence of the effect of evaporation driven by increasing surface air temperatures. If we compare the range of projected change in the mean annual rainfall (from $-15.0\%$ to $+6.1\%$) and groundwater recharge (from $-32.3\%$ to $+5.4\%$), we see that the range of projected change in groundwater recharge is larger.

**Projection of groundwater storage**

Figure 5 shows the historical and projected simulations of mean monthly groundwater storage averaged over the whole UCP. In general, the groundwater storage gradually decreases during the dry season but responds noticeably to groundwater recharge during the wet season, reaching a peak in September (one month after the maximum rainfall in August). The figure illustrates the variation in the historical simulation and the future projections (average of the projections from the three GCMs for four climate scenarios), as well as a band of one-standard-deviation about the historical simulation.

The deviation range was calculated from the historical simulation. Due to the lack of data and knowledge regarding the response of groundwater recharge and storage to climate change (Toews and Allen, 2009; Green et al., 2011; Kurylyk and MacQuarrie, 2013), a one-standard-deviation range was assumed in this study to represent natural variation. The initial conditions (dashed lines) for each particular simulation were taken from the mean groundwater storage in 1985 (historical simulation; black dashed line) and in 2025 (projected simulations; green, orange, pink, and red dashed lines for the RCP 2.6, 4.5, 6.0, and 8.5 scenarios, respectively). They were the groundwater storage at the end of the five-year pre-simulation periods for both historical run (1981–1985) and projection run (2021–2025), respectively.

In the historical simulation, the groundwater storage varied from 69.5 km$^3$ in April to 73.6 km$^3$ in September. Comparing the four projections (average from three GCMs) with the historical simulation, we see that decreases in the mean monthly groundwater storage are projected for all scenarios. The impact of climate change can be assessed based on the relative change in groundwater storage (difference in value between the initial and mean monthly groundwater storages). Supplement Figure S7 shows the temporal variation and relative change compared to the initial condition in groundwater storage for twelve different experiments using three GCMs forced by four changing climate conditions. According to the relative change in groundwater storage, it was clear that all twelve experiments showed decreasing groundwater storage relative to initial conditions for all months of the year except August to October. The most pronounced decrease of approximately 1.25 km$^3$ (from January to March) in groundwater storage was detected in the HadGCM under the RCP6.0 scenario, which was the lowest projection in groundwater recharge scenario.

Figure 6 shows the relationship between the percentage reduction in groundwater recharge and the changes in mean annual groundwater storage projected with the nine experiments that showed a decreasing trend in groundwater recharge. The results are not surprising, considering that the projection patterns of rainfall and groundwater recharge varied predominantly by GCM (see circle dashed lines in Figure 6). However, under the projection we can see an envelope of reduction in groundwater storage, which was the results from only three GCMs, ranging from 1.20 to 2.20 km$^3$ for reductions in groundwater recharge ranging from 3.2 to 32.3%. This relationship clearly shows agreement between relative change in groundwater storage and recharge.

**Overall discussion regarding to limitation of the projected results**

The projection of climate variables, groundwater recharge and storage were conducted under four climate scenarios with three GCMs out of 45 GCMs (as of September 2013) that have been studied in climate change models (Jones, 2013). This study focused on the regional scale, therefore the bias correction method that applied to GCM data is a source of uncertainty. For instance, a relative shifting and scaling technique does not correct biases in rainfall intensity; more weak rainfall events in GCMs could result in higher interception loss, causing lower groundwater recharge. Thus, the results derived from the three GCMs used could be altered if more GCMs were considered.

Our projection was focused on the near future in order to avoid the effect of land use change, thus the signal of climate change in some experiments showed different directions in the target period. Hence, natural variability in the modeled climate in the specific ensemble is large, leading
to opposing trends between RCP6.0 and other scenarios in groundwater recharge in the MIROC (Supplement Figure S6). This is also the cause of the groundwater change not being proportional to the emission scenario severity in the other GCMs.

CONCLUSIONS

The projected changes in groundwater resources vary primarily by GCM rather than by climate scenario. However, decreases in both groundwater recharge and storage were projected for almost all scenarios. The relative changes in groundwater storage confirm that future climate change will cause a reduction in groundwater resources. A groundwater recharge–storage–reduction relationship was constructed to estimate the change in groundwater recharge in the UCP as a function of storage under climate change conditions.

This study is the first projection of groundwater recharge and storage covering the entire UCP using the latest greenhouse gas emission scenarios. The large ranges in the projections of groundwater recharge and storage reveal the influence of the choice of GCM and scenario that is inevitable when using climate projection models (Döll, 2009; Kurylyk and MacQuarrie, 2013). An assessment should be conducted with an appropriate technique, such as a probabilistic approach or multi-model ensemble technique, to better quantify and reduce the uncertainty in these projections (Kurylyk and MacQuarrie, 2013). However, the probable range of impacts of climate change on groundwater recharge and storage in the UCP was evident in this study. The results demonstrate that the selection of a global climate model influences the projections in both direction and magnitude. Further projections with uncertainty analysis are needed to improve our qualitative understanding of groundwater resources and to quantitatively project the effects of climate change on groundwater resources with a high degree of confidence.

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SUPPLEMENTS

S1. Soil Moisture Deficit method
S2. Setting groundwater flow model boundaries and simplification of an aquifer layer to calculate groundwater storage
S3. Validation of river discharge at the C.2 basin outlet station
S4. Spatial distribution of groundwater level
Figure S1. Study area: (a) map of Thailand and location of the study area (b) Upper Chao Phraya River basin (UCP)
Figure S2. Groundwater recharge occurrence
Figure S3. Comparison between the simulated and observed mean monthly river discharge at the C.2 basin outlet gauging station during the period 1986–2000. The light blue shaded area represents a band of one standard deviation
Figure S4. Spatial distribution of the groundwater observation wells in the Lower Yom and Nan River basin
Figure S5. Comparison of spatial distribution of groundwater basins between geo-hydrological site investigation by the Department of Groundwater Resources and the groundwater flow model result (color shading; historical simulation)
Figure S6. Spatial variation of mean annual groundwater recharge (the values in parentheses indicate projected changes in the percentage relative to the reference period)
Figure S7. Temporal variation of mean monthly groundwater storage and relative change in groundwater storage for twelve different experiments under four scenarios of three GCMs. Initial condition of groundwater storage considered in each experiment was a mean groundwater storage in 2025, end year of five year pre-simulation period (2021–2025)
Figure S8. Spatial variation of mean groundwater levels: dry month (left) and wet month (right)
Table S1. Mean annual rainfall, runoff, evaporation, and air temperature for both the reference period (1986–2000) and projection period (2026–2040)

REFERENCES

Alcamo J, Flörke M, Märker M. 2007. Future long-term changes in global water resources driven by socio-economic and climate changes. *Hydrological Sciences Journal* **52**: 247–275. doi: 10.1623/hysj.52.2.247.
Department of Groundwater Resources. 2011a. The integrated conjunctive groundwater and surface water use and the pilot groundwater resources management in northern region of Thailand. Final report (in Thai), Bangkok, Thailand; 290.
Department of Groundwater Resources. 2011b. The study and survey of hydro-geological map (1:50,000) of the Upper Chao Phraya groundwater basin, zone III (Nakhon Sawan, Tak, and Kamphaeng Phet provinces). Final report (in Thai), Bangkok, Thailand; 1310.
Department of Groundwater Resources. 2011c. Pilot study and experiment on managed aquifer recharge using ponding system in the lower north region river basin, Pitsanulok, Sukhothai, and Pichit provinces. Final report (in Thai), Bangkok, Thailand; 420.
Department of Groundwater Resources. 2012. The study and survey...
of hydro-geological map (1:50,000) of the Upper Chao Phraya groundwater basin, zone I (Uttaradit, Sukhothai, and Lampang provinces). Final report (in Thai), Bangkok, Thailand: 450.

Department of Water Resources. 2007. Strategic plan for water resources management in 25 basins. Final report (in Thai), Bangkok, Thailand: 397.

Döll P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. Environmental Research Letters 4: 035006. doi: 10.1088/1748-9326/4/3/035006.

Gleeson T, Wada Y, Bierkens M, van Beek L. 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488: 197–200. doi: 10.1038/nature11295.

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock HM, Kanae S. 2012. H08 regional application: Case study of global aquifers revealed by groundwater footprint. Journal of Hydrology 405: 532–560. doi: 10.1016/j.jhydrol.2011.05.002.

Hanasaki N, Mateo C. 2012. H08 regional application: Case study of the Chao Phraya River. H08 supplemental documentation 1; 25.

Hanasaki N, Kanae S, Oki T, Sud YC. 1998. Design of total runoff integrating pathways (TRIP)-A global river channel network. Earth Interact 2: 1–37. doi: 10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2.

Oki T, Sud YC. 1998. Design of total runoff integrating pathways (TRIP)-A global river channel network. Earth Interact 2: 1–37. doi: 10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2.

Prickett TA, Lonnquist CG. 1971. Selected digital computer techniques for groundwater resource evaluation. Illinois State Water Survey, Bulletin 65: 62.

Ramanrong V, Wongsawat S. 1999. Groundwater resources in Thailand (in Thai). Chulalongkorn University, Bangkok, Thailand; 174.

Robock A, Vinnikov KY, Schlosser CA, Speranskaya NA, Xue YK. 1995. Use of midlatitude soil moisture and meteorological observations to validate soil moisture simulations with biosphere and bucket models. Journal of Climate 8: 15–35. doi: 10.1175/1520-0442(1995)008<0015:UMSMTS>2.0.CO;2.

Rushton KR, Ward C. 1979. The estimation of groundwater recharge. Journal of Hydrology 41: 345–361. doi: 10.1016/0022-1694(79)90070-2.

Scibek J, Allen DM. 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. Water Resources Research 42: W11405. doi: 10.1029/2005WR004742.

Toews MW, Allen DM. 2009. Evaluating different GCMs for predicting spatial recharge in an irrigated arid region. Journal of Hydrology 374: 265–281. doi: 10.1016/j.jhydrol.2009.06.022.

van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose S. 2011. The representative concentration pathways: An overview. Climatic Change 109: 5–31. doi: 10.1007/s10584-011-0148-z.

Walton WC, Ackroyd EA. 1966. Effects of induced streambed infiltration on water levels in wells during aquifer tests. University of Minnesota Water Resources Research Center Bulletin 2; 43.