Effect of Climate Change on Groundwater Age of Thailand’s Lower Chao Phraya Basin

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Abstract. Water is indispensable for life, including groundwater that the largest fresh water source. Groundwater sustainability is threatened by many factors, one is climate change which lead to flood and drought. Groundwater age is an indicator that can be applied for vulnerability assessment and sustainable groundwater management. This research focus on the changing of groundwater age under the effect of climate change using the steady-state three-dimensional mathematical simulation including, MODFLOW-2000 and MODPATH. In addition, the climate scenario including, IPSL-CM5A-MR that consist the increasing of carbon dioxide (Representative Concentration Pathways; RCP) between 2.6, 4.5 and 8.5 in the period 2017-2036. The results revealed groundwater age was highly distributed between 140 to 177,505 years with the average 18,665 years due to the distribution of groundwater recharge and pumping in the basin. In addition, the average groundwater age with RCP 2.6, 4.5 and 8.5 were decreased to 17,217, 15,960, 16,286 years from base case (18,665 years), respectively. Because the quantity of rainfall which contribute the hydraulic head, hydraulic gradient and velocity was changed. In conclusion, the groundwater sustainability in the Lower Chao Phraya basin was consistent during this period because the groundwater age was decreased by rainfall. However, the old groundwater, non-renewable groundwater could be conservative due to the distribution of groundwater age was increased.

1. Introduction
Water resource is the important resource for alive. Especially, Groundwater is the largest fresh water source in the world but the increasing of carbon-dioxides gas in the atmosphere affect the global and local climate change. Additionally, the global climate change affects the world the agricultures and water resource (Ali et al., 2012 [1]; Kumar, 2014 [2]; Pholkern et al., 2018 [3]). So, plants, food and water are become low quality and may be facing the shortage which is the anxious situation.

The global climate change highly effects the tropical climate in term of groundwater quality and quantity, sustainability and vulnerability assessment (Green et al., 2011 [4]; Taylor and Callist, 2012 [5]; Chris et al., 2012 [6]; White and Tony, 2012 [7]). Thailand located in the tropical climate. Then, groundwater resource in Thailand may be facing these problems. Several researches investigated the climate change effect on groundwater resources for example, Saraphirom et al. (2013) [8], Srisk and Nettasana (2017) [9]; Tanachaichoksirikun et al. (2018) [10]. Although, the research about the
groundwater management for groundwater sustainability under the global climate change is very important, the indicators of groundwater management are not approached.

Groundwater age is the time elapsed since the water molecule entered the groundwater basin until the water molecule located in the interesting position (Cook and Herczeg, 2000 [11]; Kazemi et al., 2006 [12]) which is useful such as, infer recharge rates (e.g. Sanford et al., 2004 [13]) and to sustainably exploit groundwater resources, analyze aquifer vulnerability (Manning and Solomon, 2005 [14]; Bethke and Johnson, 2008 [15]; Molson and Frind, 2012 [16]; Zhu et al., 2016 [17]; Sonnenborg et al., 2016 [18]) and understand the complex flow system (Troldborg et al., 2008 [19]; Ebert et al., 2012 [20]). Tanachaichoksirikun and Seeboonruang (2015) [21] reported the average age of groundwater was inclined, although the young and old groundwater age was mixed. Because the quantity of older groundwater was higher than the younger groundwater, however, the effect of groundwater pumping decreased groundwater age, the old groundwater may be was extracted. Although, the groundwater age is excellent indicator of groundwater, it never used to describe the effect of climate change.

Thailand’s Lower Chao Phraya (LCP) basin was selected for this research by three reasons 1) it is the largest groundwater basin in Thailand and also located in the central part of Thailand that cover Bangkok (Capital City of Thailand). 2) there are a lot of groundwater monitoring stations, the calibration and verification are efficient. 3) this area faced the groundwater over-extraction, its effect contributed to the land subsidence. These reasons show that the LCP basin is important for groundwater management. Then, if the correlation between climate change and groundwater age is determined, the groundwater planning for vulnerability and sustainability will be efficient.

Then, this current research investigated the groundwater age under the effect of variable climate change of the Thailand’s Lower Chao Phraya Basin to evaluate the changing and sensitivity of groundwater age and suggest the preliminary groundwater management under the effect of climate change.

2. Material and method

2.1. Modelling framework

The solution approach to steady-state groundwater flow equation and particle tracking are present here. The general form of the equation for groundwater flow over the physical dimension is

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y \frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z \frac{\partial h}{\partial z}\right] + W = 0 \quad (1)$$

where $K_x, K_y, K_z$ are the hydraulic conductivity in $x, y, z$ dimension, respectively (LT$^{-1}$), $h(x, y, z, t)$ is the hydraulic head (L), $W$ is sink or source (L$^3$T$^{-1}$/L$^3$).

Additionally, the solution of the particle tracking equation over the physical dimension is

$$\begin{align*}
(x_p)_{t_2} &= x_1 + \frac{1}{A_x} \left[ (v_{x_p})_{t_1} e^{(A_x \Delta t - v_{x_1})} \right] \quad (2a) \\
(y_p)_{t_2} &= y_1 + \frac{1}{A_y} \left[ (v_{y_p})_{t_1} e^{(A_y \Delta t - v_{y_1})} \right] \quad (2b) \\
(z_p)_{t_2} &= z_1 + \frac{1}{A_z} \left[ (v_{z_p})_{t_1} e^{(A_z \Delta t - v_{z_1})} \right] \quad (2c)
\end{align*}$$

where $x_p, y_p, z_p$ are the last position of particle (L), $x_1, y_1, z_1$ are the initial position of particle (L), $A_x, A_y, A_z$ are velocity gradient, $v_x, v_y, v_z$ are velocity in $x, y, z$ dimension, respectively.

In this research, Modular Finite-Difference Ground-water Flow Model-2000; MODFLOW-2000 (Harbaugh et al., 2000 [22]) was selected to determine the groundwater flow field. Because the application and determination described groundwater flow in the complex problem. In addition, A Particle-Tracking Model for MODPATH version-6 (Pollock, 2012 [23]) was carried out to report the moving and age of groundwater due to the conservative of groundwater age and efficient for determine the changing of groundwater age.
2.2. Study area

Thailand’s Lower Chao Phraya (LCP) basin locates in the central plain, which cover 21 provinces including, Bangkok. The shape like triangle which the tip is in Chai Nat province and widespread to Chao Phraya delta region near the Gulf of Thailand. The plain is approximately 230 km from the east-west and about 300 km for the north-south, the total area of 43,317 km² (Fig. 1.). The western bounds the Tenasserim hills. The northern is connected to the Upper Chao Phraya basin which Chao Phraya river connected. The eastern part is series of small hill. The south side is near to the Gulf of Thailand. The area consists 4 major rivers i.e., Chao Phraya, Pa Sak, Tha Chin and Mae Klong rivers. The basin is relatively flat with water flow from the north to south.

The hydrogeological of the Lower Chao Phraya basin is sedimented from the Tertiary to Quaternary strata of Lower Central Plains. The groundwater system consists of sand, gravel and lensed of clay of Pliocene-Pleistocene-Holocene age. The aquifers are predominantly old flood-plain 8 principal confined aquifers with 30-70 m thick. The top subsurface is overlain by the Bangkok Clay with 10-20 m. The total depth of the groundwater system is approximately 500 meters. The 2nd (Phra Pradeang; PD), 3rd (Nakorn Luang; NL), 4th (Nonthaburi; NB) aquifers that the major groundwater pumping wells for consumption agriculture and industry were focused in this research. Since the groundwater was over-extracted, the subsequence land subsidence was occurred in this area.

The climate records of Lower Chao Phraya monitoring stations during 1983-2014 indicated that the average annual rainfall had increased from 1,191 mm (1983-1998) to 1,208 mm (1999-2014) and the average temperature had increased from 27.1 °C (1983-1998) to 27.4 °C (1999-2014).

The projected climate scenario weather data during 2017-2036 was generated by Wattanasetpong et al. (2015) [24] based on 30 years weathering records of Thailand’s Lower Chao Phraya monitoring stations. The six criteria which consist the annual rainfall, average temperature, pressure, humidity, evaporation and groundwater discharge were selected because they are the important climate change factor. In this research, Ruangrassamee et al. (2015) [25] described the climate scenario IPSL-CM5A-MR that was developed by the Institute Pierre Simon Laplace offered the minimum root mean square error and minimum bias in the Chao Phraya watershed. So, this model was chosen. Additionally, the Representative Concentration Pathways (RCP) was selected between 2.6, 4.5 and 8.5 because the quantity of carbon dioxide gives the contrasted of the quantity of rainfall.

![Figure 1. Topographical map of LCP basin (Tanachaichoksirikun et al., 2018 [10])](image-url)
2.3. Methodology

2.3.1 Groundwater simulation

2.3.1.1 Model construction and boundary conditions
The LCP basin was distributed to nine strata including, eight aquifers and the top stratum was Bangkok clay (BKC) which individually discretized to 350 × 300 (row × column) with grid size of 1 × 1 km². The constant head was applied in the south for the Gulf of Thailand. The north was constant for groundwater flux from Upper Chao Phraya basin. The river boundary was applied for 4 rivers. the others were no-flow boundary. In addition, the climate was treated as recharge boundary and the groundwater extraction was treated as pumping boundary.

2.3.1.2 Groundwater parameters
The groundwater parameter is an important, but the numerical groundwater model cannot determine directly. So, the inverse simulation needs to be performed the groundwater parameters; effective porosity (\(\Phi\)), horizontal hydraulic conductivity (\(K_h\)), and vertical conductivity (\(K_v\)). The groundwater parameters were shown in the Table 1.

| Aquifers         | \(\Phi\)   | \(K_h\) (m/s) | \(K_v\) (m/s) |
|------------------|------------|---------------|---------------|
| Bangkok Clay     | 0.03       | 1x10^{-8} - 1x10^{-9} | 1x10^{-8} - 1x10^{-9} |
| Bangkok          | 0.2 - 0.3  | 5x10^{-5} - 6x10^{-6} | 5x10^{-9} - 6x10^{-10} |
| Phra Pradeang    | 0.25 - 0.35| 2x10^{-5} - 7x10^{-6} | 2x10^{-9} - 7x10^{-10} |
| Nakorn Luang     | 0.2 - 0.35 | 1x10^{-4} - 6x10^{-6} | 1x10^{-8} - 6x10^{-10} |
| Nonthaburi       | 0.3 - 0.35 | 2x10^{-4} - 7x10^{-6} | 2x10^{-8} - 7x10^{-10} |

2.3.1.3 Calibration and Verification
The calibration and verification of the groundwater model were illustrated in the Figure 2. In the calibration model, the simulated hydraulic heads were compared to the measured hydraulic heads in the period 2009-2014. The absolute residual mean error was 4.59 m. and the root mean squared error was 5.38 m. and the normalized root mean squared error was 5.91%. In addition, the verification model, the simulated hydraulic heads were compared to the measured hydraulic heads in the period 2007-2008.

![Figure 2](image-url)
The absolute residual mean error was 2.58 m and the root mean squared error was 3.77 m and the normalized root mean squared error was 3.82%.

2.3.2 Modelling scenarios

The climate scenario, IPSL-CM5A-MR consists the Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5. The average annual rainfall of the scenarios based on the period 2017-2036 were 1,182, 1,258 and 1,227 mm, under RCP 2.6, 4.5 and 8.5, respectively, while the annual rainfall has the increasing trend by 1.85, 2.64 and 12.78 mm/year, respectively. Then IPSL-CM5A-MR with RCP 4.5 has the greatest annual rainfall while IPSL-CM5A-MR with RCP 8.5 has the highest trend of annual rainfall in this period.

The base case period (2009-2014) was used as the control model for check the effect of climate change on the groundwater age of Thailand’s LCP basin. Additionally, the research was suggested the groundwater sustainability assessment in the basin. In the climate scenario which is IPSL-CM5A-MR of RCP 2.6, 4.5 and 8.5, monthly precipitation was average during 2017-2036. The assessment was analyzed with regard to the reaction of groundwater age. In addition, the groundwater extraction in the future was assumed the same pumped at the base case. Because the area has the low increasing pumping rate during this period.

2.3.3 Particle tracking

The particles which assume as the water molecule were randomly assigned in the PD NL and NB layers. The backward tracking was analyzed because it easy to compare with the existing research that groundwater was tracked at the observation location. In addition, the predicted groundwater age was tracked by varied the climate scenarios and backward tracking method. Because the changing of groundwater age was affected the groundwater location of and velocity.

3. Results and discussion

3.1 Observed and modelled age

Table 2. shows the simulated groundwater age in the Lower Chao Phraya basin and comparing with Sanford and Buapeng (1996) [26] age. the average groundwater age in the PD, NL and NB aquifers were 6,031, 12,466 and 33,325 years and the average age was 18,665 years. The average groundwater age can comparable with Sanford and Buapeng (1996) [26] that the absolute error 7.58%. In addition, groundwater age which computed by MODPATH-6 (Pollock, 2012 [23]) was higher distributed than Sanford and Buapeng (1996) [26] age because the starting point of particles were randomly distributed all of the model domain while the starting point of Sanford and Buapeng (1996) [26] age located at the observation well in the model.

Table 2. Simulated groundwater age in the LCP basin

| Aquifers | Sanford and Buapeng (1996) [26] model | MODPATH-6 | Average age |
|----------|------------------------------------|------------|-------------|
| PD       | 4300-35000                         | 180-31281  | 6031        |
| NL       | 10500-40000                        | 140-74959  | 12466       |
| NB       | 12100-34700                        | 215-177505 | 33325       |
| Average  | 20195                              |            | 18665       |

3.2 Projected groundwater age

Table 3. shows the predicted groundwater age in the Lower Chao Phraya basin under the base case (2009-2014) and the variable climate change (IPSL-CM5A-MR) including RCPs 2.6, 4.5 and 8.5 with the PD, NL and NB aquifers. the finding revealed the groundwater age were decreased from 18,665 to 17,217, 15,960 and 16,286 years under the IPSL-CM5A-MR with RCPs 2.6, 4.5 and 8.5, respectively.
Because the largest average rainfall which contribute the hydraulic head, hydraulic gradient and groundwater velocity, the velocity direct effects on the groundwater age. In addition, the distribution of groundwater in PD, NL and NB aquifers was decreased due to the distribution of groundwater recharge and pumping in each aquifer. Moreover, the average groundwater age in each aquifer was decreased from base case indicating, the groundwater in this period still sustainable.

| Climate       | Groundwater age (years) | Mean |
|---------------|-------------------------|------|
|               | PD         | NL     | NB     |      |
| Base Case     | 180-31281 | 140-74959 | 215-177505 | 18665|
| Average       | 6031      | 12446  | 33325  |
| IPSL RCP 2.6  | 189-30838 | 124-58148 | 212-152495 | 17217|
| Average       | 6347      | 12308  | 34792  |
| IPSL RCP 4.5  | 192-19713 | 123-72311 | 214-151586 | 15960|
| Average       | 5756      | 11593  | 32210  |
| IPSL RCP 8.5  | 191-20385 | 122-72040 | 213-144167 | 16286|
| Average       | 5834      | 11684  | 33064  |

4. Conclusion
This research has investigated the effect of variable climate on the groundwater age and the preliminary suggestion of Thailand’s Lower Chao Phraya (LCP) basin. The climate scenario which IPSL-CM5A-MR was varied Representative Concentration Pathway (RCP) between 2.6, 4.5 and 8.5 during periods 2017-2036. The simulations were performed using MODFLOW-2000 and MODPATH in steady-state condition. The findings revealed that the average groundwater age was decreased. Specifically, in the simulation IPSL-CM5A-MR RCP 4.5 had the lowest average age as a result of the largest average rainfall which contribute the hydraulic head, hydraulic gradient and groundwater velocity. the velocity direct effects on the groundwater age. In addition, the Lower Chao Phraya basin had the higher distribution of groundwater age due to the distribution of groundwater recharge and pumping in the area. Moreover, the average groundwater age was lower than the groundwater age in the past indicating, the groundwater in the basin still sustainable during this period (2017-2036). However, the old groundwater, non-renewable groundwater could be conservative due to the distribution of groundwater age was increased. Additionally, this research was carried the particle tracking (MODPATH) model that dispersion and diffusion were ignored.

5. References
[1] Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I, Hodgson G and Charles S 2012 Potential climate change impacts on groundwater resources of south-western Australian Australia J. Hydrol. 475 456–472
[2] Kumar C P 2014 Impact of climate change on groundwater resources Handbook of research on climate change impact on health and environmental sustainability 196–221
[3] Pholkern K, Saraphirom P and Srisuk K 2018 Potential impact of climate change on groundwater resources in the Central Huai Luang Basin, Northeast Thailand Sci. Total Environ. 633 1518–1535
[4] Green, T R, Taniguchi M, Kooi H, Gurdak J J, Allen D M, Hiscock K M, Treidel, H and Aureli A 2011 Beneath the surface of global change: Impacts of climate change on groundwater J. Hydrol. 405 532–560
[5] Taylor R and Callist T 2012 The impacts of climate change and rapid development on weathered crystalline rock aquifer systems in the humid tropics of sub-Saharan Africa: Evidence from south-western Uganda Clim. Chang. Eff. Groundw. Resour. A Glob. Synth. Find. Recomm. 17–32
[6] Chris M H, Harm D, Diana M A and Dirk K 2012 Groundwater recharge and storage variability in southern Mali Clim. Chang. Eff. Groundw. Resour. A Glob. Synth. Find. Recomm. (London: United Kingdom)

[7] White I and Tony F 2012 Reducing groundwater vulnerability in Carbonate Island countries in the Pacific Clim. Chang. Eff. Groundw. Resour. A Glob. Synth. Find. Recomm. 75–110

[8] Saraphirom P, Wirojanagud W and Srisuk K 2013 Potential Impact of Climate Change on Area Affected by Waterlogging and Saline Nagarajan Nagarani, Arumugam Kuppusamy Kumaraguru, Velmurugan Janaki D EnvironmentAsia 77 19–28

[9] Srisuk K and Nettasana T 2017 Climate change and groundwater resources in Thailand J. Groundw. Sci. Eng. 5 67–75

[10] Tanachaichoksirikun P, Seeboonruang U and Saraphirom P 2018 Impact of climate change on the groundwater sustainability in the Lower Chao Phraya Basin, Thailand Proc. 4th Int. Conf. Eng. Applied Sci. Technol. 119–122

[11] Cook P G and Herczeg 2000 A environmental tracers in subsurface hydrology Kluwer Academic Publishers (Boston: USA)

[12] Kazemi G A, Lehr J H and Pierre P 2006 Groundwater Age. John Wiley & Sons

[13] Sanford W E, Plummer L N, Mcada D P, Bexfield L M and Anderholm S K 2004 Hydrochemical tracers in the middle Rio Grande Basin, USA:2. Calibration of a groundwater-flow model Hydrogeol. J. 12 389–407

[14] Manning A H and Solomon D K 2005 An integrated environmental tracer approach to characterizing groundwater circulation in a mountain block Water Resour. Res. 41 1-18

[15] Bethke C M and Johnson T M 2008 Groundwater age and groundwater Age dating Annu. Rev. Earth Planet. Sci. 36 121–152

[16] Molson J W and Frind E O 2012 On the use of mean groundwater age, life expectancy and capture probability for defining aquifer vulnerability and time-of-travel zones for source water protection J. Contam. Hydro. 127 76–87

[17] Zhu Y, Shi L, Wu J, Ye M, Cui L and Yang J 2016 Regional quasi-three-dimensional unsaturated-saturated water flow model based on a vertical-horizontal splitting concept Water 8

[18] Sonnenborg T O, Scharling P B, Hinsby K, Rasmussen E S and Engesgaard P 2016 Aquifer vulnerability assessment based on sequence stratigraphic and 39Ar transport modeling Ground Water 54 214–230

[19] Trolldborg L, Jensen K H, Engesgaard P, Refsgaard J C and Hinsby K 2008 Using environmental tracers in modeling flow in a complex shallow aquifer system J. Hydrol. Eng. 13 1037–1048

[20] Eberts S M, Böhlke J K, Kauffman L J and Jurgens B C 2012 Comparison of particle-tracking and lumped-parameter age-distribution models for evaluating vulnerability of production wells to contamination Hydrogeol. J. 20 263–282

[21] Tanachaichoksirikun P and Seeboonruang U 2015 Preliminary study on exposure time model for groundwater age in Lower Chao Phraya Basin Proc. The 6th National Convention on Water Resour. Eng. (NCWRE6) 1–12

[22] Harbaugh A W, Banta E R, Hill M C and McDonald M G 2000 MODFLOW-2000, The U.S. Geological Survey modular ground-water model-user guide to modularization concepts and the ground-water flow process

[23] Pollock D 2012 User guide for MODPATH version 6: a particle tracking model for MODFLOW: Tech. Methods 6–A41 58

[24] Wattanasetpong J, Charoenvaravut P and Laosinwattana W 2012 Downscaling climate models in Thailand by artificial neural network method Thesis of Civil Eng. KMITL (Bangkok: Thailand)

[25] Ruangrassamee P, Khamkong A and Chuenchum P 2015 Assessment of precipitation simulations from CMIP5 climate models in Thailand Proc. The 3rd EIT Int. Conf. on Water Resour. Eng. (ICWRE3) 1-9

[26] Sanford W E and Buapeng S 1996 Assessment of a ground water flow model of the Bangkok Basin, Thailand, using carbon 14 based ages and paleohydrology Hydrogeol. J. 4 26–40
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