Unconfined Groundwater Storage Change over the Greater Chao Phraya River Basin

Phanith Kruy[1] and Piyatida Ruangrassamee[1,*]

[1] *Department of Water Resources Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, THAILAND*
**Corresponding author; E-mail address: Piyatida.H@chula.ac.th*

Abstract

Groundwater monitoring network is essential to monitor groundwater levels and usage, however, it requires relatively high capital and human resources. Advanced land surface modeling and data assimilation techniques using ground based observations and satellite products provide complementary information concerning space and time for groundwater change Global Land Data Assimilation System version 2.2 (GLDA-v2.2) provides daily groundwater storage (GWS) products from 2003 to present for unconfined aquifers. This study aims to analyze monthly groundwater storage change over the Greater Chao Phraya River basin between 2009 to 2018 using data from the monitoring wells with their screen depth less than 30 meters for validation. The Mann-Kendall test was used to analyze GWS trends. Based on the GWS from GLDAS-v2.2 the GWS in the transition zone from the upper to the lower part of the Greater Chao Phraya River basin (around Kamphaeng Phet, Phichit, Sukhothai, and Nakhon Sawan provinces) is lower compared to the GWS in the northern part of the Greater Chao Phraya River basin. The estimated GWS from the observed water table level is based on the water table fluctuation (WTF) method (GWS_{WTF}). The correlation coefficient between GWS_{GLDAS} and GWS_{WTF} is greater than 0.7. Overall, GWS_{GLDAS} is underestimated compared to GWS_{WTF}. According to the Mann-Kendall Test, the groundwater storage has significant change ($p < 0.05$) in most of the Greater Chao Phraya River basin except during the transition period (TS). The GWS in the northern part of the Greater Chao Phraya River basin around Chiang Mai, Lamphun, Lampang, Phrae, and Phayao provinces shows higher depletion compared to the lower part of the Greater Chao Phraya River basin. For seasonal change, the highest depletion occurred during the southwest monsoon (SW) with the depletion rate of 3.4 mm/month, followed by depletion during Northeast monsoon (NE) which is 3.0 mm/month. For the transition period (TS), the depletion rate is 2.5 mm/month. The analysis of monthly data shows that the highest annual GWS depletion is 1.2 mm/month. The increasing trend occurred around Samut Sakhon, Bangkok, Pathum Thani, and Nakhon Nayok provinces. The rate of increasing trend in those provinces is up to 0.50 mm/month.

Keywords: groundwater storage, GLDAS, trend analysis, Chao Phraya River basin

1. Introduction

Groundwater use has become more important, especially in the region where water is scarce and unreliable. Over exploitation of groundwater leads to storage depletion and water insecurity. Groundwater storage fluctuations are generally driven by natural factors (rainfall, vegetation, soil types), and anthropogenic (socioeconomic concerns, land use/land cover change, damming) processes with complex, nonlinear interactions between them [1,2]. In the case of Thailand, when surface water supplies became insufficient to meet rapidly increasing water demands, a number of wells were drilled to supplement the water supply. This led to the decline of groundwater level, and it mostly happened in the lower Chao Phraya River basin since 1950s [3]. After that, groundwater usage has become more strict under the Groundwater Act [4] and is regulated only by the Ministry of Natural Resources and Environment through the Department of Groundwater Resources (DGR). The extensive network of monitoring groundwater levels had been established by the DGR. However, the monitoring wells with available long term and continuous data are still limited. Much progress has been made with groundwater storage estimation using remotely sensed data [5-8]. Li, et al. [8] reviewed various studies and demonstrated that terrestrial water storage anomalies obtained from the Gravity Recovery and Climate Experiment (GRACE) mission have shown great promises for estimating groundwater storage changes in various regions, but the application of GRACE is also limited by its low spatial resolution which is about 150,000 km^2. The estimated groundwater storage changes derive from GRACE, Global Land Data Assimilation System (GLDAS) products are used to combine with the terrestrial water storage anomalies from GRACE [6,7,9]. The latest GLDAS-v2 has three components: GLDAS-v2.0, GLDAS-v2.1, and GLDAS-v2.2 which have been developed by the NASA Goddard Space Flight Center (GSFC) Hydrological Sciences Laboratory (HSL) and the Goddard Earth Sciences Data and Information Services Center (GES DISC) [10].

GLDAS-v2.2 is added to the GES DISC archive, and it includes a main product from the Catchment Land Surface Model (CLSM-F2.5) with Data Assimilation for the Gravity Recovery and Climate Experiment (GRACE-DA). There are 24 parameters including groundwater storage. The groundwater storage from GLDAS-v2.2 is daily groundwater storage (GWS) which is available from 2003 to present for unconfined aquifers. Dubey, et al. [11] used groundwater storage from GLDAS-v2.2 products to investigate groundwater use in India.

This study aims to use groundwater storage from GLDAS-v2.2 to analyze monthly groundwater storage change over the Greater Chao Phraya River Basin between 2009 to 2018. The validation of groundwater storage from GLDAS-v2.2 was carried out using the data from the monitoring wells of the Department of Groundwater Resources (DGR). The trend analysis of seasonal and annual groundwater storage change was carried out using Mann-Kendall test.

2. Data and Methodology

2.1 Groundwater storage from GLDAS-v2.2

NASA Global Land Data Assimilation System Version 2 (GLDAS-2) has three components including GLDAS-v2.0, GLDAS-v2.1, and GLDAS-v2.2. The GLDAS-v2.0 is forced entirely with the Princeton meteorological forcing input data and provides a temporally consistent series from 1948 through 2014. GLDAS-v2.1 is forced with a combination of model and observation data from 2000 to present. The GLDAS-v2.2 uses the conditions from the GLDAS-v2.0 Daily Catchment model simulation. The GLDAS-v2.2 is forced with the meteorological analysis fields from the operational European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System but the total terrestrial water anomaly observation from Gravity Recovery and Climate Experiment (GRACE) is assimilated [5]. The GLDAS-v2.2 data product contains 24 land surface fields including groundwater storage. More detail about GLDAS-v2.2 and data are publicly available from https://disc.gsfc.nasa.gov/datasets/GLDAS_CLSM025_DA1_D_2.2/summary.

In this study, the daily GWS is from GLDAS-v2.2 dataset at the spatial resolution of 0.25° from 2009 - 2018. The GWS is estimated as water column with a unit of "mm". For the groundwater storage trend analysis over the Greater Chao Phraya River basin, Mann-Kendall test was used. The time series of monthly GWS was calculated from the daily average of each month and year. Seasonal GWS based on Thai Meteorological Department (TMD) is shown in Table 1. The trend of seasonal GWS change was analyzed by using Mann-Kendal (MK) test.

Table 1 The season based on TMD [12]

J	F	M	A	M	J	J	A	S	O	N	D
NE	TS			SW					NE		

*NE: Northeast Monsoon, TS: Transition Season, SW: Southwest Monsoon

Monthly GWS anomaly is calculated from Eq (1) where ***i*** denotes month, ***j*** denotes year, and ***length(j)*** denotes a number of years used in the analysis.

$$GWSA_{monthly,GLDAS} = GWS_i - \frac{\sum GWS_{i,j}}{length(j)} \tag{1}$$

Where i = month, j = year

2.2 Estimation of groundwater storage anomalies based on the water table fluctuation (WTF) method

Estimated groundwater storage from observed water table level has been adopted from Chen, et al. [6], Wang, et al. [7] and Cao, et al. [13]. The core principle of the WTF method is that the groundwater storage anomalies is equal to the recharge of groundwater over long-time interval and can be calculated by Eq (2).

$$\Delta GWS_{WTF} = S_f \times \Delta h \tag{2}$$

Where S_f is the specific yield of the aquifer and Δh is the groundwater head anomaly within a specific time interval. The monthly Δh of a single monitoring well refers to the anomaly between the average water level of each month and the average water level of all months of the monitoring well. Because of the lack of aquifer-specific yield distribution maps in the study area, the specific yield of the aquifer was determined based on the information of aquifer's formation where the monitoring well locates. With these two parameters, the estimated groundwater storage anomaly can be determined.

Groundwater level data used in this study are from the Department of Groundwater Resources (DGR), Thailand. The groundwater level is measured from the ground surface to water level of each monitoring well. The information of aquifer's formation was obtained from the Department of Mineral Resources (DMR), Thailand as shown in Fig. 1. The different materials in the aquifer's formation shown in Table 2, are used to calculate the specific storage of the aquifer where the monitoring well located. For example, the fluvial deposit aquifer which is classed by DMR is composed from gravel, sand, silt, and clay having the average S_f approximately 23%, 24%, 18%, and 2% respectively. The specific storage of the fluvial deposit is the average S_f of gravel, sand, silt, and clay.

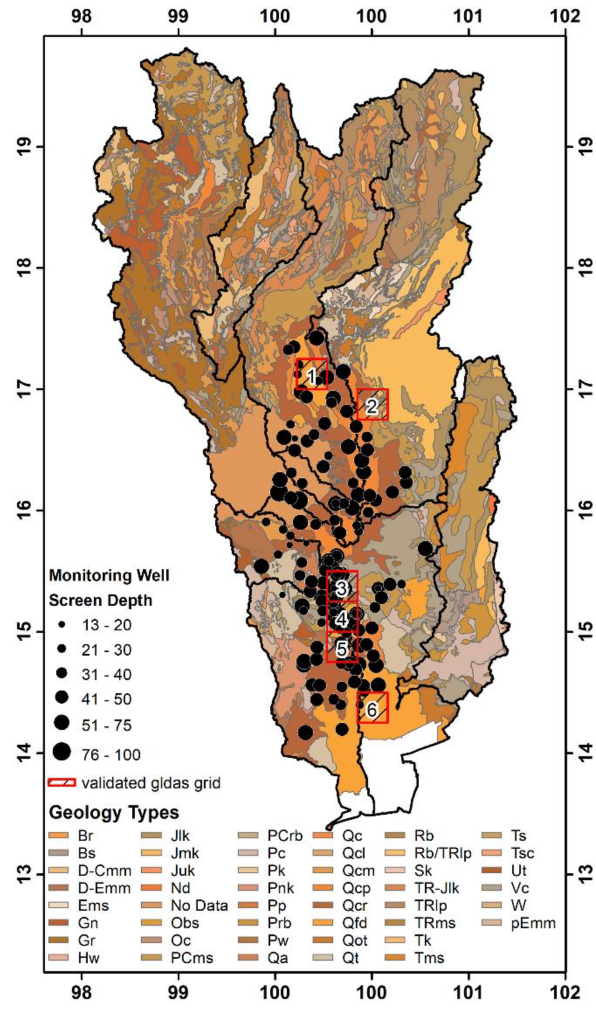

Fig. 1 Geology map over the Greater Chao Phraya River basin

Table 2 Specific yields for different formation (source: Johnson [14])

Formation	S_y (%)	$S_{y,avg}$ (%)
Clay	0-5	2
Sandy Clay	3-12	7
Silt	3-19	18
Fine sand	10-28	21
Medium sand	15-32	26
Coarse sand	20-35	27
Gravelly sand	20-35	25
Fine gravel	21-35	25
Medium gravel	13-26	23
Coarse gravel	12-26	22

GWS from GLDAS-v2.2 was validated using the estimated GWS from the selected monitoring wells of DGR with screen depth less than 30 m, which is assumed to be approximately in unconfined aquifers. The red squares in Fig. 1 are the GWS_{GLDAS} grids which were selected for the validation. The correlation coefficient was calculated using Eq (3) as follows:

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \tag{3}$$

Where x_i is the estimated GWS_{WTF} and y_i is GWS_{GLDAS}.

2.3 Groundwater storage trend analysis

The nonparametric Mann-Kendall (MK) test is a statistical significance test that does not require data in a particular distribution [11].

The statistic of the MK trend test, **Z**, is expressed as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}}, S > 0 \\ 0, S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}}, S < 0 \end{cases} \tag{4}$$

Where:

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i) \tag{5}$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1, \theta > 0 \\ 0, \theta = 0 \\ -1, \theta < 0 \end{cases} \tag{6}$$

$$\operatorname{var}(S) = n(n-1)(2n+5)/18 \tag{7}$$

Where x_k and x_i are the sequential data values for groundwater storage, and n is the length of the data.

The index for measurement of trend, i.e., the inclination is expressed as Eq (8) as follows:

$$\beta = median\left(\frac{x_i - x_j}{i - j}\right) \qquad (8)$$

β denotes rising trend Where $1 < j < i < n$, A positive β denotes rising trend, while a negative β denotes decreasing trend. The significance level is considered with the alpha α= 0.05.

3. Results and Discussion

3.1 Spatial and temporal distribution of GWS

Fig. 2 illustrates the monthly and seasonal average groundwater storage from GLDAS-v2.2 over 10 years (2009-2018) over the Chao Phraya River Basin. The highest average GWS is observed in September, October, and November and the GWS has decreased during the transition period, especially in April and May for both upper and lower of the Greater Chao Phraya River basin. The groundwater storage in the transition zone from the upper to the lower part of the Greater Chao Phraya River basin (around Kamphaeng Phet, Phichit, Sukhothai, and Nakhon Sawan provinces) is lower compared to the GWS in the northern part of the Greater Chao Phraya River basin (Fig. 2).

3.2 Validation of GWS from GLDAS-v2.2

GWS from GLDAS-v2.2 was validated using the estimated GWS from the selected monitoring wells of DGR with screen depth less than 30 m, which is assumed to be approximately in unconfined aquifers. The red squares in Fig. 1 are the GWS_{GLDAS} grids that were selected for the validation.

Fig. 3 shows the comparison between the available in situ groundwater levels converted to the estimated GWS anomaly (GWS_{WTF}) using the water table fluctuation (WTF) method and the time series of the GWS from GLDAS-v.2.2 (GWS_{GLDAS}) from 2009 – 2018. Only the estimated monthly GWS_{WTF} based on the available data from the monitoring wells and the corresponding GWS_{GLDAS} were used for the validation. The validation shows that the correlation coefficient between GWS_{GLDAS} and GWS_{WTF} from the selected grids and monitoring wells is greater than 0.7 on average. For the interpretation of acceptable range of correlation coefficient, it is arbitrary. However, the correlation coefficient in the range around 0.7 can be considered moderate to good. While the GWS_{GLDAS} has a good relationship with the shallow monitoring well, GWS_{GLDAS} is underestimated compared to GWS_{WTF}.

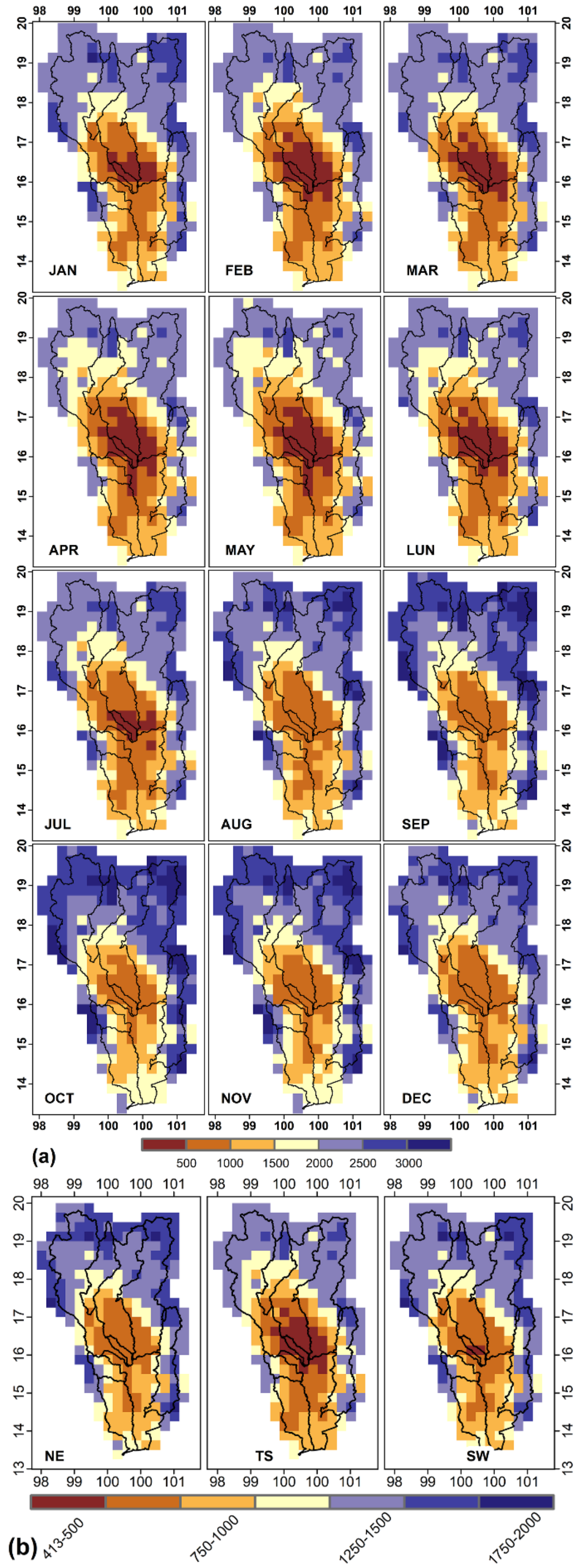

Fig. 2 Map of average (a) monthly (b) seasonal average of GWS in mm from GLDAS-v2.2 from 2009-2018

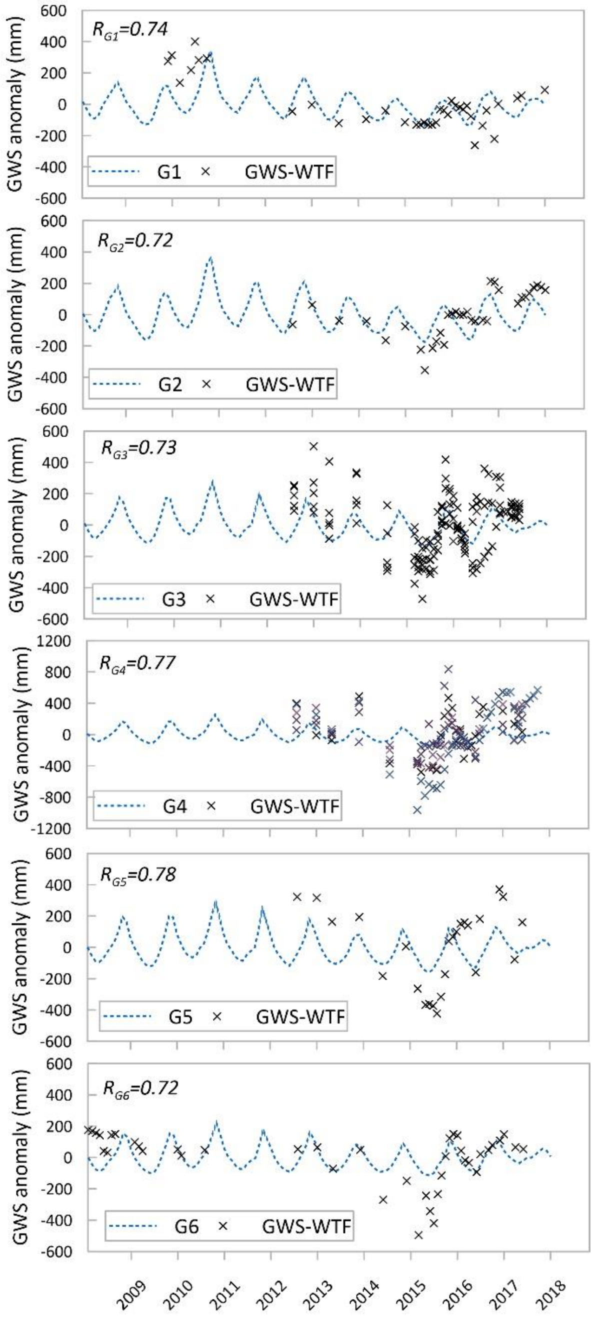

Fig. 3 Time series of GWS_{GLDAS} and available data of GWS_{WTF}

3.3 Groundwater storage change

Based on the significance test from the Mann-Kendall test with α=0.05, the storage changes were determined and demonstrated as the spatial depletion map in Fig. 4. The annual and seasonal changes are shown in Fig. 5. The groundwater storage in the Northern part of the Greater Chao Phraya River basin around Chiang Mai, Lamphun, Lampang, Phrae, and Phayao provinces shows higher depletion trend compared to the lower part of the Greater Chao Phraya River basin. For seasonal change, the highest depletion occurred during the Southwest Monsoon (SW) with a depletion rate of 3.4 mm/month, followed by the Northeast Monsoon (NE) with a depletion rate of 3.0 mm/month. For the transition period (TS), the depletion rate is 2.5 mm/month.

The analysis of monthly data shows that the highest annual groundwater storage depletion is 1.2 mm/month. The increasing trend occurred around Samut Sakhon, Bangkok, Pathum Thani, and Nakhon Nayok provinces. The rate of increasing trend in those provinces is up to 0.50 mm/month.

According to the Mann-Kendall test, the groundwater storage has significant change ($p < 0.05$) in most of the Greater Chao Phraya River basin except during the transition period (TS). The map of the p-value is shown in Fig. 6.

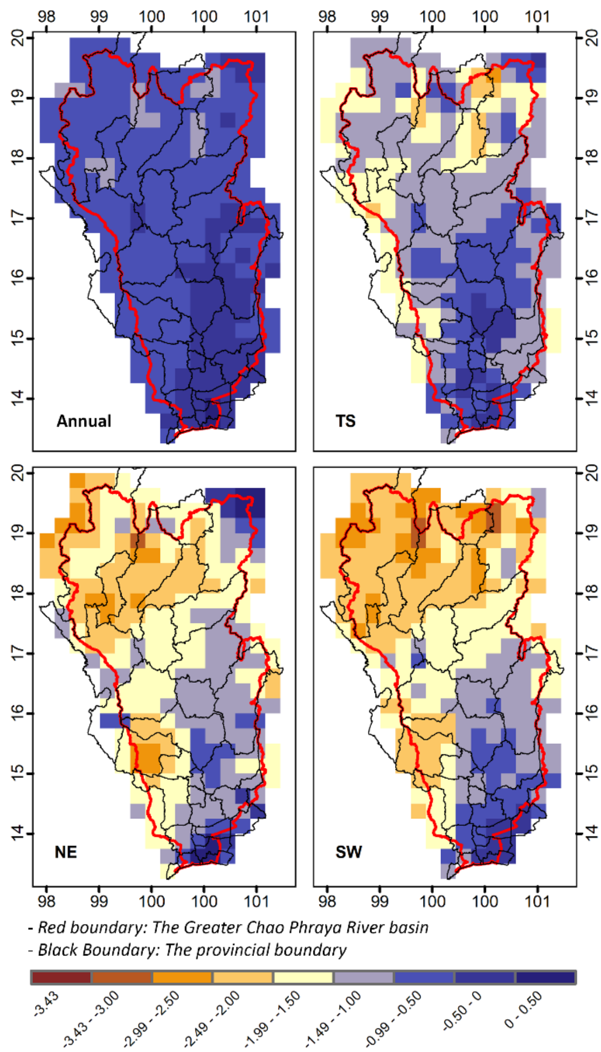

Fig. 4 Map of average groundwater storage change (mm/month) during 2009-2018

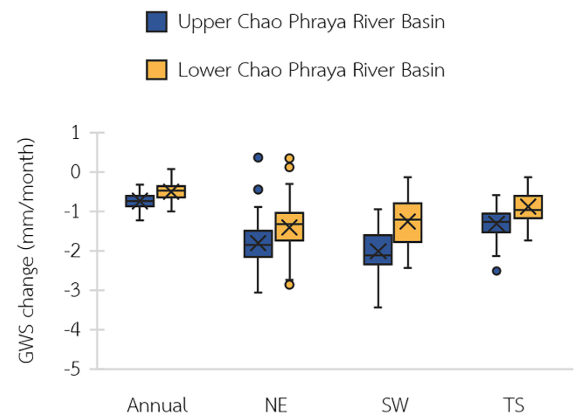

Fig. 5 Average groundwater storage change during 2009-2018

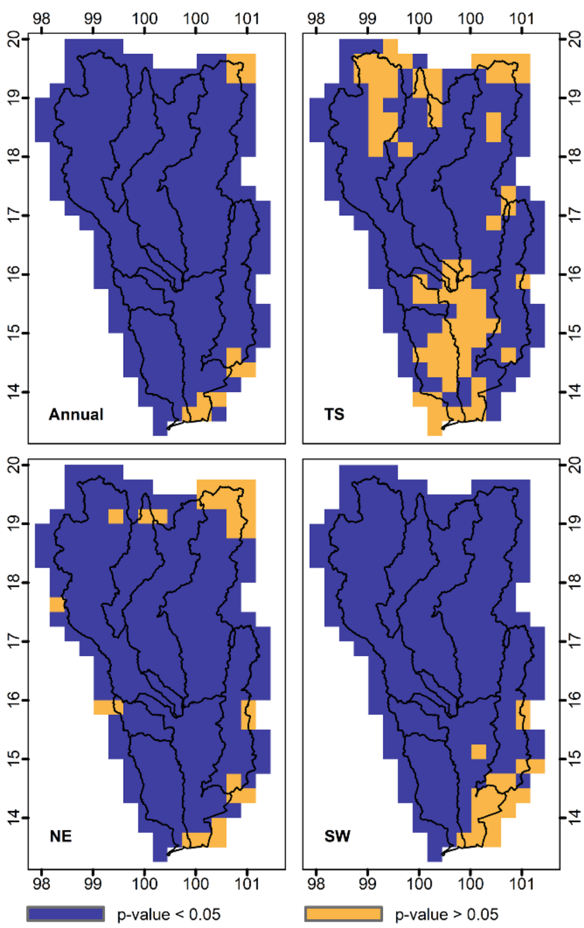

Fig. 6 P-value of groundwater storage change

4. Conclusions

Groundwater monitoring network is essential to monitor groundwater levels and usage. However, the monitoring wells with available long-term and continuous data are still limited. Advanced land surface modeling and data assimilation techniques using ground based observations and satellite products provide complementary information concerning space and time for groundwater change. This study uses groundwater storage from GLDAS-v2.2 to analyze monthly groundwater storage change over the Greater Chao Phraya River Basin between 2009 to 2018. The correlation coefficient between GWS_{GLDAS} and GWS_{WTF} is greater than 0.7. Overall, GWS_{GLDAS} is underestimated compared to GWS_{WTF}. Based on the GWS from GLDAS-v2. 2, the groundwater storage in the transition zone is lower compared to the GWS in the northern part of the Greater Chao Phraya River basin. It was found that groundwater storage has a significant trend ($p<0.05$) in most of the Greater Chao Phraya River basin except during the transition period (TS). The groundwater storage in the northern part of the Greater Chao Phraya River basin shows higher depletion compared to the lower part. For seasonal change, the depletion rate during the Southwest Monsoon (SW) is slightly higher than the Northeast Monsoon (NE). The increasing trend occurred around Samut Sakhon, Bangkok, Pathum Thani, and Nakhon Nayok provinces. Groundwater storage depends on both natural and anthropogenic processes. The results from this study only provide the spatial distribution of groundwater storage change in unconfined aquifers based on GLDAS data. Further study to analyze the relative impact of each natural and anthropogenic factor needs to be carried out to identify key factors impacting groundwater storage change in each area.

There are several limitations and uncertainties in GLDAS data. The GWS_{GLDAS} can only capture groundwater storage in shallow aquifer. The anthropogenic processes are not considered in the model yet. For groundwater monitoring networks, available data are limited and not continuous. In the process of estimating groundwater storage from groundwater level, there is uncertainty in parameter range based on the geology. The applicability of GLDAS-v2.2 is shown in this study and further validation needs to be carried out where groundwater monitoring network data are available.

Acknowledgement

Phanith Kruy is supported by Chulalongkorn University's Graduate Scholarship Programme for ASEAN or Non-ASEAN Countries. This research is part of the research project “Water security assessment based on development of water management system using technology in central region and the Eastern Economic Corridor” under NRCT Spearhead Research Program on Water Management supported by National Research

Council of Thailand. We thank the Department of Groundwater Resources, Thailand for groundwater level data.

References

[1] Saikia, P., Kumar, A., Diksha, Lal, P., Nikita, and Khan, M. L. (2020). Ecosystem-Based Adaptation to Climate Change and Disaster Risk Reduction in Eastern Himalayan Forests of Arunachal Pradesh, Northeast India, in *Nature-based Solutions for Resilient Ecosystems and Societies*, S. Dhyani *et al.* Eds. Singapore: Springer Singapore, pp. 391-408.

[2] Lambin, E. F., Geist, H. J., and Lepers, E. (2003). Dynamics of Land-Use and Land-Cover Change in Tropical Regions. *Annu Rev Env Resour,* vol. 28, no. 1, pp. 205-241.

[3] Babel, M. S., Gupta, A. D., Domingo, N. D. S., and Donna, N. (2006). Land subsidence: A consequence of groundwater over-exploitation in Bangkok, Thailand. *International Review for Environmental Strategies,* vol. 6, no. 2, pp. 307-327.

[4] Fornés Azcoiti, J. M. and Pirarai, K. (2014). Groundwater in Thailand.

[5] Li, B., Rodell, M., Sheffield, J., Wood, E., and Sutanudjaja, E. (2019). Long-term, non-anthropogenic groundwater storage changes simulated by three global-scale hydrological models. *Sci Rep-Uk,* vol. 9, no. 1, p. 10746.

[6] Chen, J. L., Wilson, C. R., Tapley, B. D., Scanlon, B., and Güntner, A. (2016). Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global Planet Change,* vol. 139, pp. 56-65.

[7] Wang, S., Liu, H., Yu, Y., Zhao, W., Yang, Q., and Liu, J. (2020). Evaluation of groundwater sustainability in the arid Hexi Corridor of Northwestern China, using GRACE, GLDAS and measured groundwater data products. *Sci Total Environ,* vol. 705, p. 135829.

[8] Li, B., Rodell, M., and Famiglietti, J. S. (2015). Groundwater variability across temporal and spatial scales in the central and northeastern U.S. *Journal of Hydrology,* vol. 525, pp. 769-780.

[9] Rodell, M., Velicogna, I., and Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature,* vol. 460, no. 7258, pp. 999-1002.

[10] GES-DISC. GLDAS Version 2 Data Products Released. https://disc.gsfc.nasa.gov/information/data-release?title=New%20and%20Reprocessed%20GLDAS%20Version%202%20Data%20Products%20Released (accessed June 16, 2022).

[11] Dubey, S. K., Lal, P., Choudhari, P., Sharma, A., and Dubey, A. K. (2022). Chapter 11 - Assessment of long-term groundwater variation in India using GLDAS reanalysis, in *Advances in Remediation Techniques for Polluted Soils and Groundwater*, P. K. Gupta *et al.* Eds.: Elsevier, pp. 219-232.

[12] TMD (2015). Climate of Thailand.

[13] Cao, Y., Nan, Z., and Hu, X. (2012). Estimating groundwater storage changes in the Heihe river basin using grace, in *2012 IEEE International Geoscience and Remote Sensing Symposium*, 22-27 July 2012 2012, pp. 798-801.

[14] Johnson, A. I. (1967). Specific yield: compilation of specific yields for various materials. (in English), *Water Supply Paper,* Report