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Flood hazard mitigation using managed aquifer recharge: Numerical assessment of a pilot trial in the Nam Kam River Basin, NE Thailand

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Abstract

Flash flooding is one of the most catastrophic natural hazards. These disastrous events may trigger some rainfall-related geohazards, e.g., landslides and slumps. Sakon Nakhon Province, partly located in the Nam Kam River Basin, has been severely damaged by storm-driven floods. Due to the effect of climate change, precipitation has changed in intensity, pattern, and frequency. In 2017, this area was hit by a tropical cyclone causing heavy rainfall and considerable flash flooding. Consequently, residential properties, agricultural areas, and infrastructure facilities were devastated. The storm eventually caused 3-million-dollar worth of damage in the province.

The challenge for policymakers is to develop strategies that can provide long-term solutions to reduce extensive damage caused by the hazards. This study drew on examples of the use of managed aquifer recharge (MAR) as an approach primarily to prevent flood-related issues and store stormwater runoff. The MAR system comprises settling and infiltration ponds constructed in an area of 8,000 m^2. A modeling approach is widely known as a scientific and reliable method for the assessment of MAR systems. Therefore, a groundwater model was developed to simulate MAR and the subsequent movement of groundwater. The MAR model was constructed using a notable 3D groundwater-flow model known as MODFLOW-NWT, in association with a MODPATH particle-tracking model. The model accounted for interactions between artificial lakes (Lak Package) and groundwater. Two model scenarios were developed based on the actual MAR methods applied at the demonstration site: (1) An infiltration pond scenario and (2) an infiltration pond with four recharge wells scenario.

The results revealed that the flow model had an acceptable accuracy with an NRMSE of 8.98%. The annual rate of pond seepage was 90,052 m^3. Additionally, artificially recharged water simulated by virtual particles could travel in the system for at least ten years, with a maximum travel distance of 698.07 meters (0.19 meters/day). In addition to recharge ponds, the runoff was recharged directly into the aquifer via the recharge wells. An annual recharge rate is about 22,600 m^3. The deeper-and-longer flow paths were roughly doubled in the distance compared to the first scenario, being up to 1,683.16 meters away from recharge wells with an average rate of 0.46 meters/day. In conclusion, the MAR system is a practical solution to capture runoff, mitigate downstream flooding, and enhance groundwater storage for sustainable water management. Most importantly, the system may provide indirect solutions for preventing geohazards within the context of river floods, landslides, and slumps.

Keywords: Flood mitigation, Groundwater model, Managed aquifer recharge

1. Introduction

Climate change has always happened on Earth and currently threatens every aspect of human being and other life on the planet. Climate-induced change involves not only increasing average air temperatures but also extreme weather events. Climate-change driven increases in water and food insecurity pose emerging and long-term challenges. Rising temperatures are already shifting precipitation patterns and intensity and may directly affect global food supply quantity and quality going forward (Phetheet et al., 2020). Moreover, under these circumstances, flood risks and water-related damages are projected to increase with every degree of warming (IPCC, 2022).

Thailand is home to almost 70 million people, which are highly dependent on agriculture and water as their primary source of income. Thailand's climate is tropical and humid, with three different seasons through most of the country. The main seasons are a dry and mild season from November to mid-March, the pre-monsoon season from mid-March to mid-May and the rainy monsoon season from mid-May to November. In Thailand, floods are the most common and recurring natural disasters and happen nearly every year during the monsoon season. Due to the effect of climate change, three important sectors of Thailand's economy, including agriculture, tourism, and trade, have been threatened recently (Kisner, 2008).

Several areas in northeast Thailand, especially in the Nam Kam River basin, have frequently suffered from floods (Fig. 1). The Nam Kam River Basin in the provinces of Sakon Nakhon and Nakhon Phanom has an average rainfall of 1,647.8 mm in 2021, which increased by 22% from 1991 (Fig. 2). In 2017, Sakon Nakhon Province was hit by flash floods on Thursday (July 27) night after heavy rains, which were considered the worst flood in 20 years that hit Isan provinces. The flooding was caused by the tropical storm "Sonca", which has caused widespread flooding throughout NE Thailand. Main roads were under nearly one meter of floodwater triggered by flash floods from the Phu Phan Mountains.

Fig. 1: (Left) An office building in Sakon Nakhon city center hit by flood. (Right) The city being submerged by flash flooding on July 28, 2017 (Charuvastra, 2017).

In 2020, the Department of Groundwater Resources (DGR), under the Ministry of Natural Resources and Environment, Government of Thailand, initiated the managed aquifer recharge (MAR) project in Sakon Nakhon and Nakhon Phanom provinces. In this paper, we focus only on a pilot MAR system in Sakon Nakhon Province. This study aims to evaluate the performance of managed artificial recharge, and to access groundwater flow characteristics and define the 3D patterns using forward particle tracking techniques through two recharge structures, including recharge wells and infiltration basins.

2. Methods

2.1 Site description

The MAR site is located in Dong Khwang Village, Dong Mafai Sub-district, Muang Sakon Nakhon District, Sakon Nakhon Province (17°4'21" N, 104°7'4" E). Sakon Nakhon's climate is classified as tropical. The wet season is oppressive and overcast, while the dry season is humid and partly cloudy. The annual average precipitation was 1,563.1 millimeters for the past five years. In July, Dong Khwang's rainfall reached 326.5 millimeters, which is roughly 150% above the

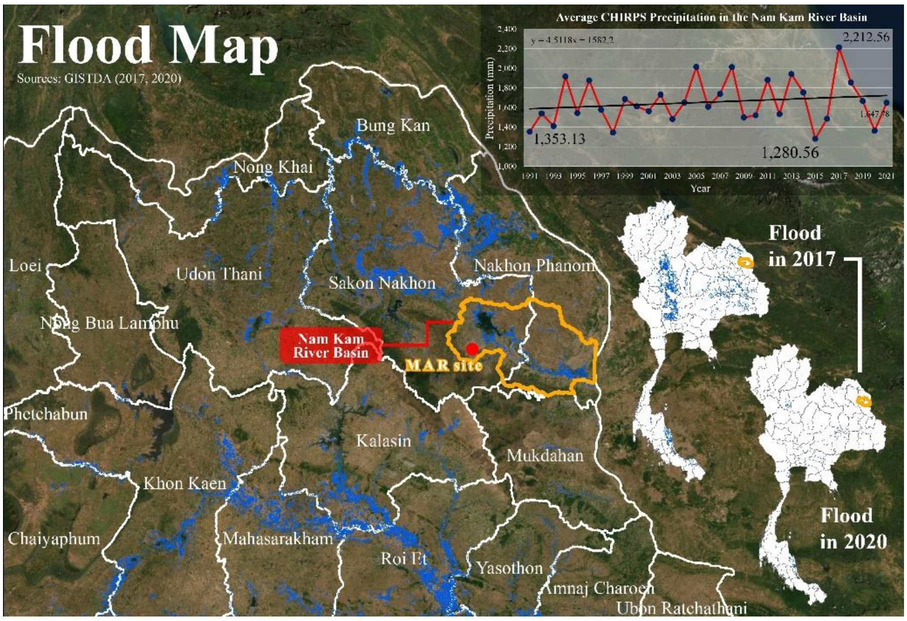


Fig. 2: Map showing flooding areas (scattered blue areas) in NE Thailand in 2017 with average annual precipitation data from 1991 to 2021 in the Nam Kam River Basin (Funk et al., 2015; GISTDA, 2017, 2020).

monthly average (Funk et al., 2015). At the Dong Khwang site, the aquifer is unconfined, and consists mainly of clayey sand, gravelly sand, and siltstone. Local groundwater level ranges from 1.14 (July 2022) to 4.06 (April 2021) meters below the surface. Seasonal groundwater-level fluctuations are approximately 2.92 meters. Hydraulic characteristics of the aquifer are 0.518 m/d, 1.66×10^{-4}, 0.437, and 0.401, for hydraulic conductivity, storativity, total porosity, and effective porosity, respectively (DGR, 2022).

The pilot MAR system at Dong Khwang site was developed in September 2021 (Fig. 3). It includes 5-meter-deep settling and recharge (infiltration) basins. The settling basin was designed to filter fine-grained sediments and minimize clogging of the successive recharge basin. It helps to improve the efficiency of the MAR system. In addition, a weir was constructed between an adjacent stream and the settling basin to control the inflow of surface water to the system. The installation of 15-meter-deep recharge wells allows water from the surface to penetrate to more permeable substrata; therefore, water can percolate directly into the aquifer. Groundwater levels were monitored monthly with six observation wells, five of which were drilled to a depth of 12 meters. The other well was installed to observe the deeper aquifer at 30 meters deep.

Fig. 3: (Left) A map showing a location of the pilot MAR trial. (Right) An aerial photo of the study area illustrating the system components.

2.2 Hydrogeological and geophysical investigation

According to previous studies, DGR published a suitability map for MAR site selection in the Nam Kam River Basin area. This MAR suitability map was implemented using GIS-based Multi-Criteria Decision Analysis (DGR, 2020). The analysis involved four main criteria, including geology, geomorphology, soil infiltration rate, and slope. As a result, Dong Khwang Village in Sakon Nakhon Province was one of the suitable sites in the Nam Kam River Basin for MAR construction.

Lithological data together with electrical well logging data were collected from the DGR's Groundwater Resources Management Database (Smart Pasutara). Additionally, six boreholes were drilled for permeability test using the falling-head test technique.

A two-dimensional resistivity survey was conducted at the MAR construction site with a spacing of 3 meters electrode (3 lines) and adjacent areas with a spacing of 10 meters electrode (15 lines). The survey aimed to characterize underlying weathering soil and bedrock at the site, and to map the horizontal and vertical variations of subsurface geology for the entire simulated area (DGR, 2022).

All primary data collected in the field and secondary information were integrated and used to construct geological and hydrogeological cross sections. These sections provide in-depth details about geological conditions, illustrate the horizontal and vertical extent of aquifers, and show the groundwater flow direction within the study area.

2.3 Simulation of pilot MAR using groundwater flow model

A groundwater-flow simulation was developed to represent the groundwater system in Dong Khwang Village, Sakon Nakhon Province. The pilot MAR scheme was simulated using the U.S. Geological Survey modular finite-difference flow model to determine the flow of groundwater through aquifers (Harbaugh, 2005). In this study, a Newton-Raphson formulation for MODFLOW-2005 called MODFLOW-NWT (Niswonger et al., 2011) was employed for solving numerical issues of the unconfined groundwater-flow equation. The MODFLOW-NWT provides an alternative solution to deal with drying and rewetting nonlinearities of the system.

The model domain represents a rectangular area of 25 km^2 (2,500 hectares) with grid sizes ranging from 50×50 to 20×20 m^2. A relatively fine-grid discretization (20×20 m^2) is required in the area of interest, such as the MAR site (Mehl et al., 2006). The groundwater model domain was discretized into 124 rows and 124 columns. The model consists of four different layers: (1) the first (uppermost) layer is of relatively low hydraulic conductivity, representing a clayey sand layer, (2) the second layer is highly permeable, being composed of gravelly sand sediments, (3) the third layer is the weathered zone of siltstone, and (4) the fourth layer is a siltstone layer (Fig. 4).

Following the conceptual model, the main input boundaries are located in the southwest from the Phu Phan Mountains, while the main output boundaries are located in northeastern part of the model boundary, where the largest natural lake of northeast Thailand, namely Nong Han, is situated. These boundaries are represented by the General-Head Boundary (GHB) package as the external boundary conditions. The top model layer involves two external surficial stresses simulated using the Recharge (RCH) and Evapotranspiration (EVT) packages. Recharge was estimated from precipitation based on the CHIRPS dataset, which is the rainfall estimates from rain gauge and satellite observations (Funk et al., 2015). The EVT values at the Sakon Nakon weather station were obtained from the Royal Irrigation Department based on reference crop evapotranspiration (ET_o) and crop coefficient (K_c). The main rivers flow from the southwestern side of the model and exit on the northeastern side, which were simulated by the River (RIV) package. Abstraction was simulated by the Well (WEL) package with the negative sign; likewise, recharge wells were calculated by the same package but applied with the opposite sign. Furthermore, the Lake (LAK) package was

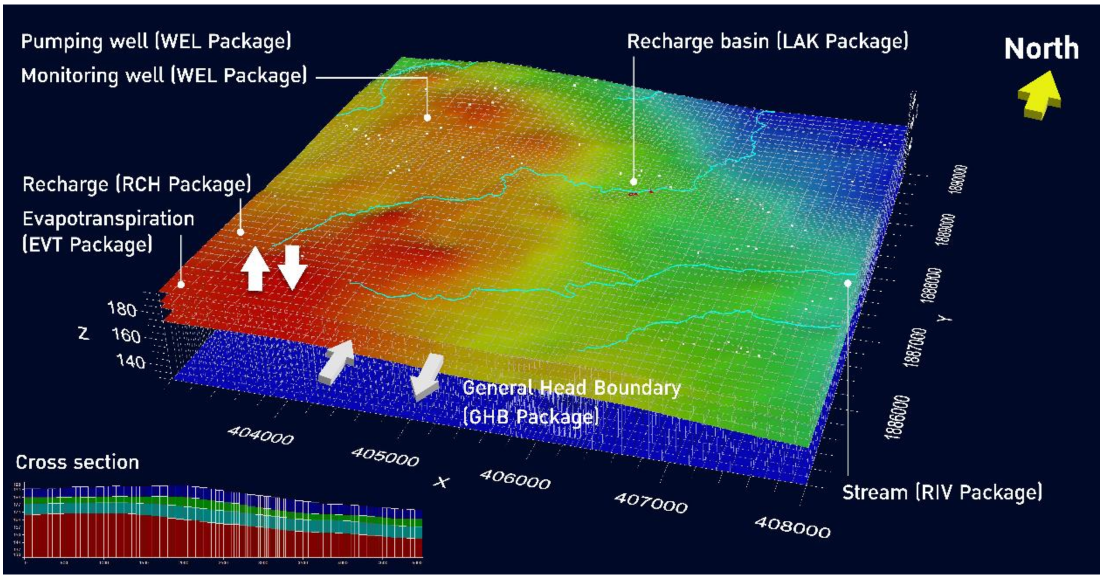


Fig. 4: A schematic diagram representing model layers and MODFLOW packages.

applied to assess the performance of the recharge basin. This package was designed to calculate volumetric water exchange between an artificial lake and an underlying aquifer (El-Zehairy et al., 2018; Merritt & Konikow, 2000). A 10-year simulation begins with monthly data from October 2020 to September 2021. For the remaining nine years (October 2021 to September 2030), input data were defined using annual average values for the projection period.

Groundwater level was monitored from 6 observation wells located around the MAR sites, and the other 71 wells were observed within the model domain. Groundwater levels were measured monthly from October 2020 to April 2022 using an electric tape and an automatic data logger. Data were used to construct head distribution and groundwater-flow direction maps. Afterward, a series of groundwater levels were imported to the model as observed head values for model validation.

After the model performance had been acceptable, MODPATH was employed to compute three-dimensional flow paths for imaginary particles of water moving through the groundwater system (Pollock, 2016). The program is known as a post-processing module that calculates flow paths from MODFLOW's head and flow output files. In addition to particle paths, MODPATH computes the residence time for particles traveling through the system.

3. Results

The results of this study are presented and discussed with the performance of the pilot MAR system. In Thailand, a modeling approach is rarely performed to investigate the dynamics of artificial lake-groundwater interactions. The MAR performance, in terms of groundwater quantity, flow direction, and residence time, will be shown and emphasized hereafter.

3.1 Groundwater flow model

Water balancing of the MAR basin involved many interacting surface, unsaturated zone, and groundwater components. In general, interactions, in terms of quantity, between the MAR system and groundwater can be simply expressed as follows:

$$P + Q_{GWin} + GHB_{in} + Well_{in} + Lake_{in} = ET + Q_{GWout} + GHB_{out} + Well_{out} + Lake_{out} + \Delta S$$

where P is precipitation rate, Q_{GWin} is stream seepage to groundwater, Q_{GWout} is groundwater seepage to stream, GHB_{in} is lateral groundwater inflows, GHB_{out} is lateral groundwater outflows, $Well_{in}$ is inflows from recharge wells, $Well_{out}$ is outflows from pumping wells, $Lake_{in}$ is seepage from the lake into groundwater, $Lake_{out}$ is seepage from groundwater into the lake

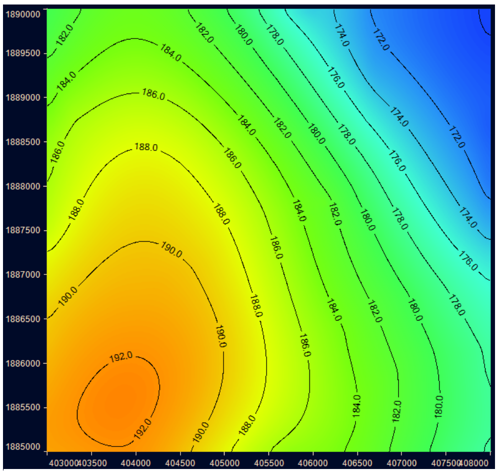
lake, ET is total evapotranspiration, and ΔS is total change in storage.

The water balance of the whole model domain is presented in Table 1. Simulated heads at different periods are shown in Fig. 5: (a) 10 days after simulation, representing the pre-MAR construction phase, (b-d) 6 months, 1 year, and 2 years after simulation, respectively. The effect of artificial recharge is presented as an increase in hydraulic head after year 1 and year 2 (Fig. 5). The calculated results showed a good match between simulated heads and observed heads, which were monitored from 77 observation wells in total, as shown in Fig. 6. The model performance was evaluated using a standard statistical parameter called the normalized root mean square error (NRMSE). The NRMSE of the pilot simulation stands at 8.98%, which was acceptable for this study. A one-year groundwater balance includes six input fluxes: storage (11.17%), wells (0.15%), river leakage (9.06%), head dep bounds (7.11%), recharge (71.90%), and lake seepage (0.61%); and six output fluxes: storage (13.87%), wells (5.54%), river leakage (15.48%), evapotranspiration (7.64%), head dep bounds (57.35%), and lake seepage (0.12%).

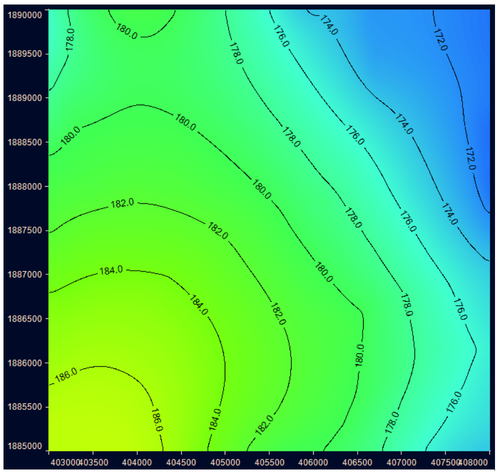
The temporal analysis of artificial lake seepage and groundwater-well recharge fluxes using MODFLOW's Lake and Well packages is the main purpose of this study. Hence, input fluxes of well and lake seepage components were considered in this study. The MAR system has an ability to store stormwater runoff as well as provide direct pathways to convey water underground. Consequently, modeling results revealed that a rate of groundwater recharge (or a seepage rate) via the infiltration basins in Dong Khwang Village was 90,052.3984 m^3 per year, while the recharge wells could supply water of about 22,599.998 m^3 to the subsurface storage in one year. A construction of the 8,000-m^2 (0.8 hectares) MAR system can store surplus water underground roughly 112,652 m^3 annually.

Table 1: Volumetric budget for the entire model at the end of 1-year simulation.

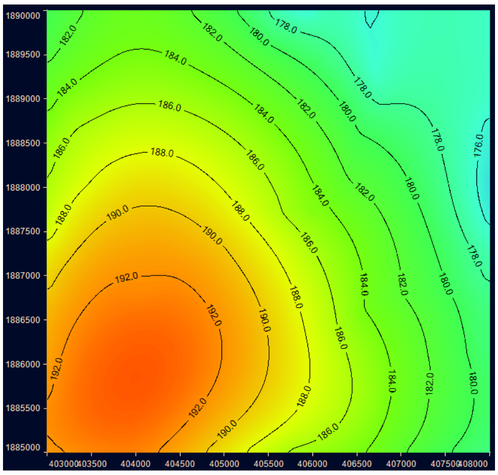
Cumulative volume (m^3)		Rates for this time step (m^3/time step)	
IN:		IN:	
Storage	1,654,455.7500	Storage	3,157.5332
Wells	22,599.9980	Wells	120.0000
River leakage	1,341,774.5000	River leakage	1,782.0767
Head dep bounds	1,052,490.1250	Head dep bounds	119.7833
Recharge	10,649,801.0000	Recharge	50,960.8984
Lake seepage	90,052.3984	Lake seepage	271.5052
Total in	**14,811,174.0000**	**Total in**	**56,411.7969**
OUT:		OUT:	
Storage	2,054,155.2500	Storage	4.2654
Wells	820,049.9375	Wells	2,310.0000
River leakage	2,293,464.5000	River leakage	13,967.9531
ET	1,131,144.1250	ET	6,022.9092
Head dep bounds	8,494,350.0000	Head dep bounds	34,106.7969
Lake seepage	18,032.5684	Lake seepage	0
Total out	**14,811,197.0000**	**Total out**	**56,411.9258**
IN - OUT	-23.0000	**IN - OUT**	-0.1289
Percent discrepancy	-0.00	**Percent discrepancy**	-0.00



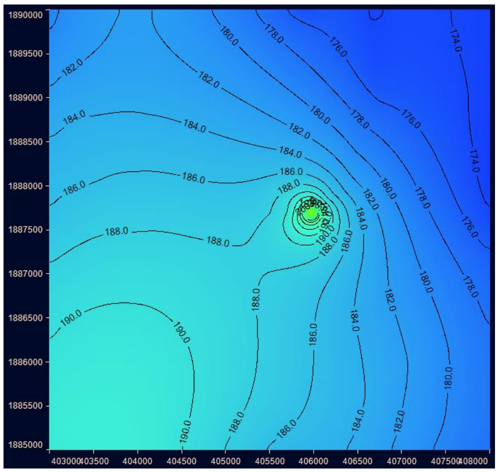
(a) 10 days after simulation
(the pre-MAR construction phase)



(b) 6 months after simulation



(c) 1 years after simulation



(d) 2 years after simulation

Fig. 5: Head distribution map (a) the pre-MAR construction phase, and (b-d) after the MAR operation at different periods.

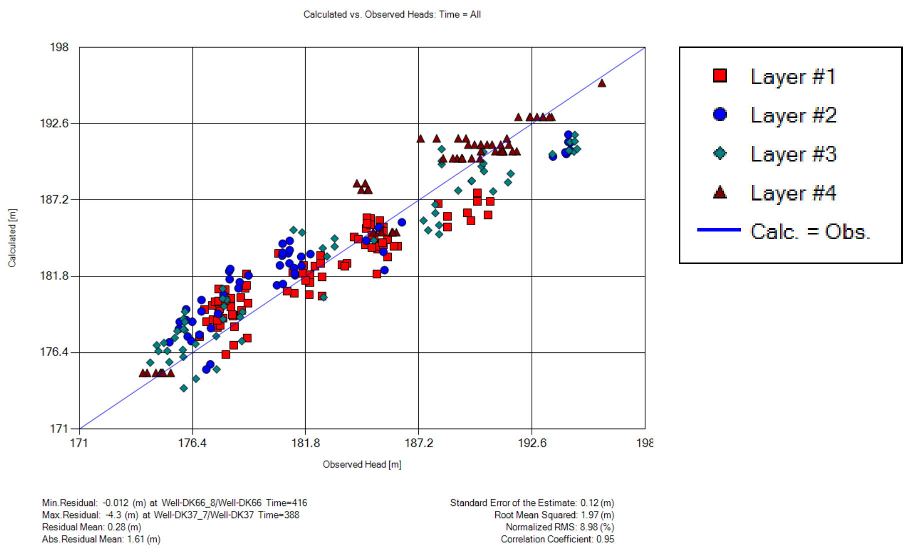


Fig. 6: Comparison between calculated heads and observed heads.

3.2 Particle-tracking model

In this study, a particle-tracking model, MODPATH, was employed to calculate 3D groundwater flow paths from the pilot MAR site (forward-particle tracking), and subsequently track the traveling time and motion of imaginary particles through the groundwater system for ten years. In the beginning, 79 particles were assigned at the bed of artificial lake, and the other 160 particles were created in the center of four 15-meter-deep recharge wells.

After a ten-year simulation, some particles exit from the aquifer after joining surface water bodies and streams. The travel distance of particles (76% of the total particles) from the infiltration ponds are mostly limited to less than 70 meters away from the site in ten years. However, 2.5% of the particles (two particles) can travel much farther, reaching a maximum distance of up to 698.070 meters. The maximum traveling rate of particles is 0.195 meters/day. However, particles simulated at a depth of 15 meters from recharge wells are much longer. Under this scenario, the maximum distance traveled by the particles is 1,683.157 meters, and the minimum distance is 177.617 meters in ten years. Hence, the traveling rate ranges from 0.05 to 0.46 meters/day.

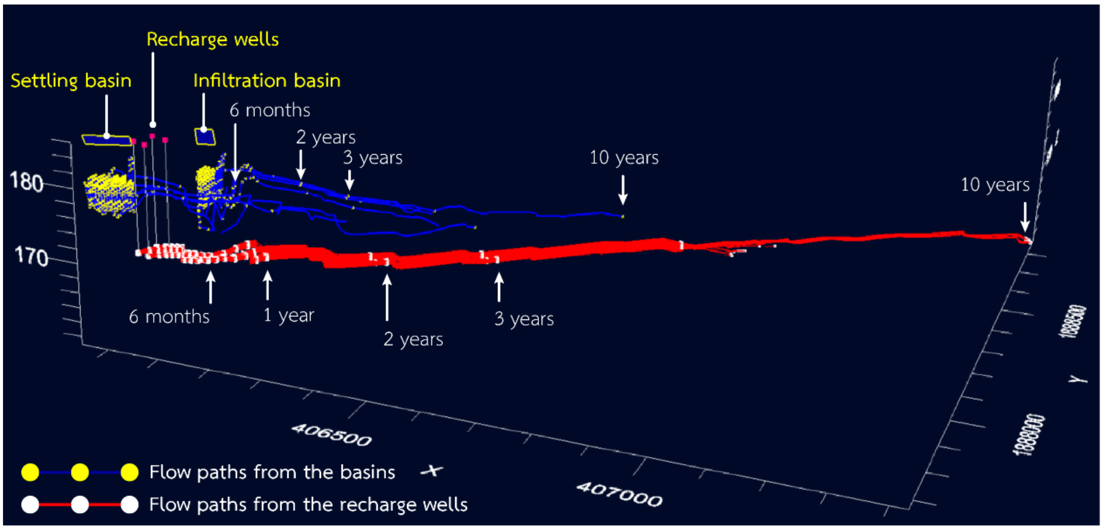


Fig. 7: Three-dimensional flow paths showing flow direction of imaginary particles from the MAR ponds (blue lines) and recharge wells (red lines).

4. Discussion

The numerical model is a simplified representation of the natural groundwater system. The model includes limitations regarding the uncertainty in hydraulic conductivity in areas far from the MAR site, the simulation of lateral groundwater fluxes across the model boundary, and the assumption of uniform storage properties. More importantly, clogging mechanisms were not included in the simulation, causing the model to produce relatively high infiltration rates via the recharge basins. Actual input data were available for one year, while the 10-year projection was assumed to be annual averages of historical data. As presented in Fig. 7, groundwater paths from the MAR basins fluctuated, conforming to seasonal changes in the water table in the first year. Afterward, particles tend to move smoothly because annual average data were applied for model projections.

However, groundwater modeling, presented in this work, is a cost- and time-saving technique to provide an accurate and adequate assessment of the MAR construction. Moreover, this technique can be adopted in any MAR system to select suitable MAR types for construction, design the system, enhance its operation, and propose water management strategies for subsequent uses of groundwater.

These facilities primarily aim to collect surplus water during the wet seasons and drain it down to the groundwater system. However, we can design the MAR system with multiple benefits, such as habitats for wildlife, which could help to make recharge basins more wildlife-friendly, increase vegetative cover, and ultimately create more soil moisture. In addition to being purpose-built recharge structures, the MAR ponds can be used as additional surface-water reservoirs, alternatively providing water for agriculture, livestock, and aquaculture for local people.

5. Conclusions

Recently, extreme precipitation events are expected to intensify with climate change and likely increase the intensity and frequency of flooding (Tabari, 2020). Floods are the deadliest and most common form of natural disaster in Thailand and the world. Floods are unpredictable; therefore, the government must be prepared to always respond.

The Department of Groundwater Resources, Ministry of Natural Resources and Environment, Government of Thailand, is an official agency with the core mission of managing groundwater resources in Thailand. After the Nam Kam River Basin faced the renowned flash flooding in 2017, DGR developed the pilot MAR system and planned to provide guidelines that will effectively mitigate the impact of climate disasters, such as flooding.

This study demonstrates the use of a renowned groundwater-flow model or MODFLOW to assess the performance of the MAR system. The results of flow simulation provide the efficiency of MAR in quantitative aspects and the projection of groundwater flow movement using forward particle tracking techniques. With an area of 0.8 hectares, the pilot MAR system is able to store stormwater runoff underground of about 112,652 m^3 per year. According to the prediction of groundwater movement and its residence time, the maximum travel distance from the MAR pond is 698.070 meters in a decade, with an average of roughly 0.195 meters/day. Particles traveling from the recharge wells, which were drilled to the highly permeable unit, can travel a longer distance. The maximum travel distance is 1,683.157 meters, with an average rate of 0.46 meters/day.

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