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Effects of Fertilization to Groundwater Contamination

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Abstract Agricultural activities have been identified as one of the major sources of groundwater pollution. The large quantities of agrochemicals discharged from the agricultural land into the water bodies had posed risks to the aquatic ecosystems and human health. Nitrate is the most common chemical contaminant discharging into the aquifer system from agricultural area. A numerical model was developed in this study to investigate the influence of fertilization on the groundwater contamination in a paddy field in Langkawi Island. The investigation on the nutrient transport was conducted by applying an instantaneous injection of nutrient to mimic the fertilization under two different scenarios: low flow condition (dry season) and high flow conditions (wet season). The results showed that the extent and transport of nutrient plume in both study cases under short-term transport simulation (≤ 1 year) was not significant. The concentration of nutrient was found to take approximately 5 years to reduce to less than 10% of its initial concentration at its release location in the study area. The relative concentration of the dispersed nutrient plume was remained at 16.7% and 8.6% under low flow and high flow condition respectively after 30 years. The results suggested that the best practice of minimizing groundwater contamination in agricultural activities is to match the fertilizer usage with the crop requirement so that the cumulative impact of nitrate leaching into the groundwater system can be reduced.

Keywords Groundwater Contamination, Groundwater Flow and Transport Modelling, Nitrate Contamination, Fertilisation

1. Introduction

Malaysia has experienced stress on water resources availability due to rapid growth in population, urbanization, industrialization, and irrigated agricultural activities. Some regions in Malaysia are facing water depletion problem despite high annual rainfall and thus groundwater has been considered as supplemental water resources from surface water in the affected areas [1]. Early investigation showed that the groundwater storage potential can reach up to 5,000 billion cubic meters in Malaysia [2]. However, inappropriate land used, and poor land management can cause issues and problems to the groundwater quality. The uncontrolled use of fertilizer and pesticide in agricultural activities has been identified as the main cause of groundwater contamination [3]. When the fertilizer application rate in the agricultural activities exceeds the uptake demand of crops, nutrient can leach into the shallow aquifer system through recharge processes induced by rainfall or irrigation. The groundwater system that connected to surface water system (i.e., river and lake) can also lead to the contamination from groundwater system into the surface water system (irrigation system) or vice versa. Previous studies have reported a direct influence of fertilization on the groundwater quality and cause the impairment to the environment and ecological system [4-6].

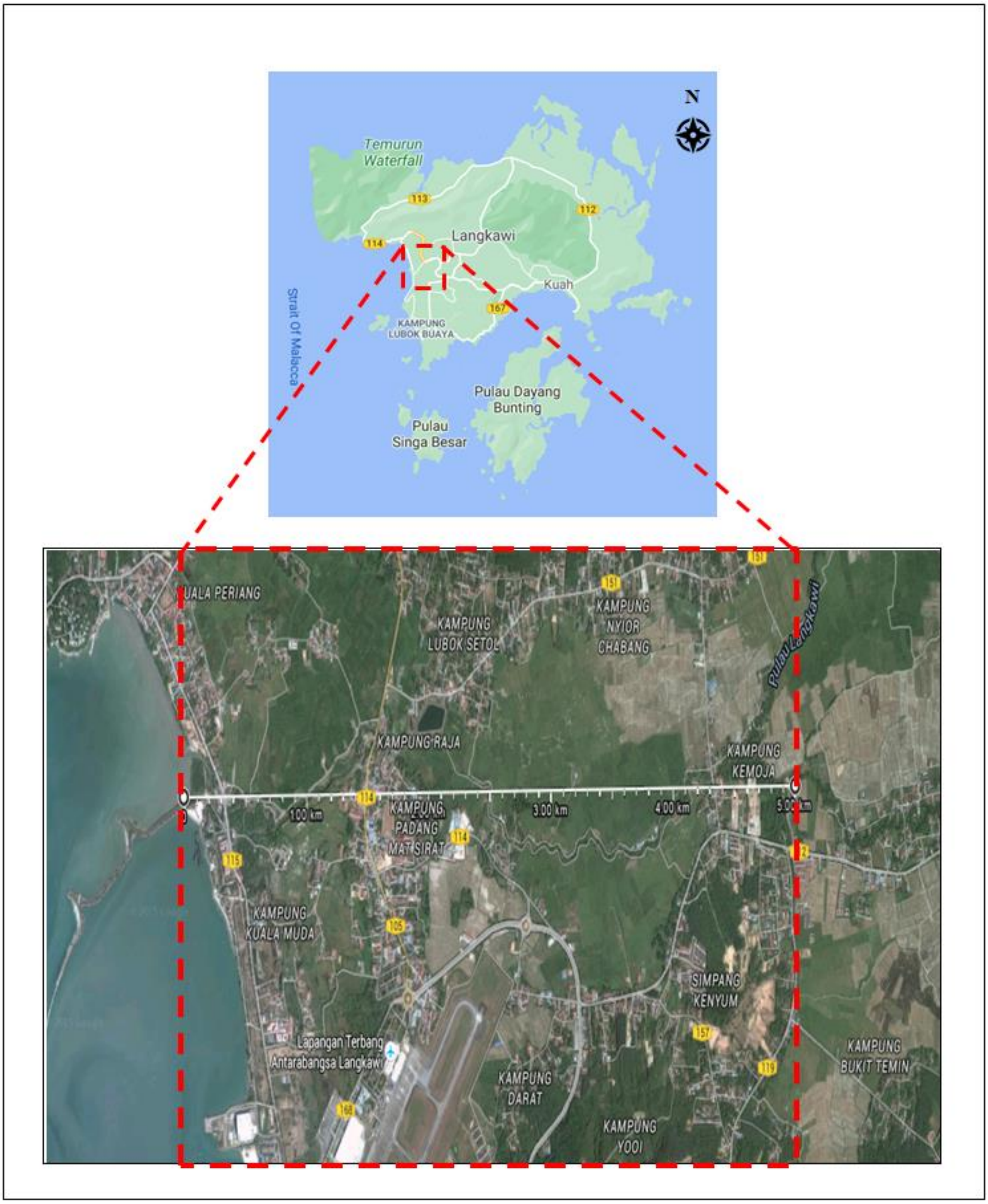


Figure 1. Study area in Langkawi Island. The numerical model domain is indicated by the red dashed lines (modified from Google Maps[13])

The forms of nutrient generally measured in groundwater contamination from agricultural activities are dominantly by nitrate (NO_3^-). Contamination occurs when the accepted minimum threshold of nitrate is exceeded in the groundwater resources. According to Malaysia Groundwater Quality and Index, the threshold value of nitrate in groundwater is 100 mg/L and 10 mg/L for consumption of livestock and raw drinking water respectively [7]. Field measurement from a paddy field in the study of Mohamed Zawawi et al. [5] reported that the average nitrate level was at 4.81 mg/L with a maximum value of 17.16 mg/L. Similar findings of nitrate contamination was reported by Jamaluddin et al. [4] and Shamsuddin et al. [8] in an intensive agricultural area in Kelantan.

Groundwater modelling has been widely used to evaluate management strategies in identifying contamination and protection of groundwater resources [9]. In this study, a paddy field located in Langkawi Island was selected as the study area. A numerical model was developed to investigate the effects of fertilization on the groundwater contamination under low flow (dry season) and high flow (wet season) conditions. The MODLOW module in Processing MODFLOW (PMWIN) was applied to simulate the groundwater flow field of the study area [10]. The nutrient fate and transport simulation was then conducted using the MT3DMS module based on the calibrated flow field model.

2. Hydrogeological Characteristics of Study Area

The study area is in the west of Langkawi Island adjacent to Langkawi Airport. The paddy field covers an area of approximately 25 km^2 and is surrounded by small settlement/villages (Figure 1). Langkawi Island is in equatorial maritime climate zone and receives an average annual rainfall of 2500 mm. The rainfall pattern is affected by south-west and north-east monsoon. This leads a wet season from April to November and dry season from December to March [11]. The study area is the largest alluvial plain in Langkawi Island. The alluvium formation of aquifer consists of silt, sand and gravel. The sand and gravel deposits are found predominantly at the northern part of the area while clayey silt covers predominantly in the southern part of this area. The thickness of the aquifer ranges from less than a meter to 30 meters [12].

3. Model Development and Calibration

The simulated study domain covered an area of 5 km × 5 km and was discretized into 100 rows x 100 columns in a single layer. The area enclosed by each cell was 50 m × 50 m. A more refined grid of 10 m × 10 m was applied to the area in transport simulation. An average thickness of 15 m was simulated as unconfined aquifer and slanted from inland to the ocean based on available hydrogeological data. The land surface slope was determined by referring to the observation wells collar elevation from the highest of 15 m to 0 m along the coastline [12]. The slope of the aquifer layer was approximately 0.003. The inland boundary was simulated as constant head boundary. The constant head at the inland boundary was assigned based on the recorded data of groundwater level in observation wells. The coastal boundary was simulated at mean sea level.

In the calibration process, the soil parameter, hydraulic conductivity was calibrated automatically using the PEST module in PMWIN [10]. The calibrated values were varied within the allowable range until a best fit of the observed and simulated hydraulic heads was achieved in the selected observation wells under steady state condition. In this process, the simulated hydraulic head was compared with the data that were obtained from the on-site observation wells in Mar 1995. The heterogeneity of the study domain was simulated by two geological formations: sandy alluvium and colluvium soil formation followed the site investigation results [12]. Two different hydraulic conductivity values were assigned respectively into two zones in the simulated model.

The percentage of differences between observed and simulated hydraulic heads was calculated using (1). The results show that both the percentages of difference for observation wells OW3 and OW4 are below 2% (0.5% and 1.6% respectively in Table 1). However, the percentages of difference for observation wells OW1 and OW2 are relatively higher, and the results show that the percentages of difference for observation wells 1 and 2 have reached 17.0% and 12.3% respectively. The differences may contribute by the heterogeneity of the soil characteristics in the area. However, the heterogeneity of the domain was represented by two geological zones; the hydraulic conductivity may vary within the zones. The hydraulic conductivity of 3.583×10^{-5} m/s and 3.475×10^{-6} m/s was assigned to the sandy alluvium and colluvium formation respectively after the calibration process. There was no data on effective porosity and the value of 0.15 was assumed in the simulation as recommended in the investigation report [12].

$$\%\,Difference = \frac{Simulated\ Hydraulic\ Head - Observed\ Hydraulic\ Head}{Observed\ Hydraulic\ Head} \times 100\% \quad (1)$$

The excessive use of nitrogen fertilizer in paddy field has been identified as the main cause in groundwater contamination [8]. In this study, Kampung Kuala Muda was selected as the study domain. The fertilizer application was simulated on an elementary plot of paddy field of 50 m width × 500 m length of area (along OBS 1-3 in Figure 2). The location was approximately 1 km from the coastline. Nine observation wells (OBS1-9 at interval of 200 m) were simulated to examine the fate and transport of the nutrient in the simulation (Figure 2). The amount of nitrate leaching to groundwater depends on the amount of fertilizer applied in excess of the amount uptake by the crop. The fertilization is a continuously process throughout the cultivation period.

Table 1. Calibration result of observed and simulated hydraulic heads.

Observation Well	Original Hydraulic head (m)	Simulated Hydraulic head (m)	Percentage of differences (%)
OW1	4.23	3.51	17.0
OW2	6.76	7.59	12.3
OW3	10.69	10.74	0.5
OW4	12.00	12.19	1.6

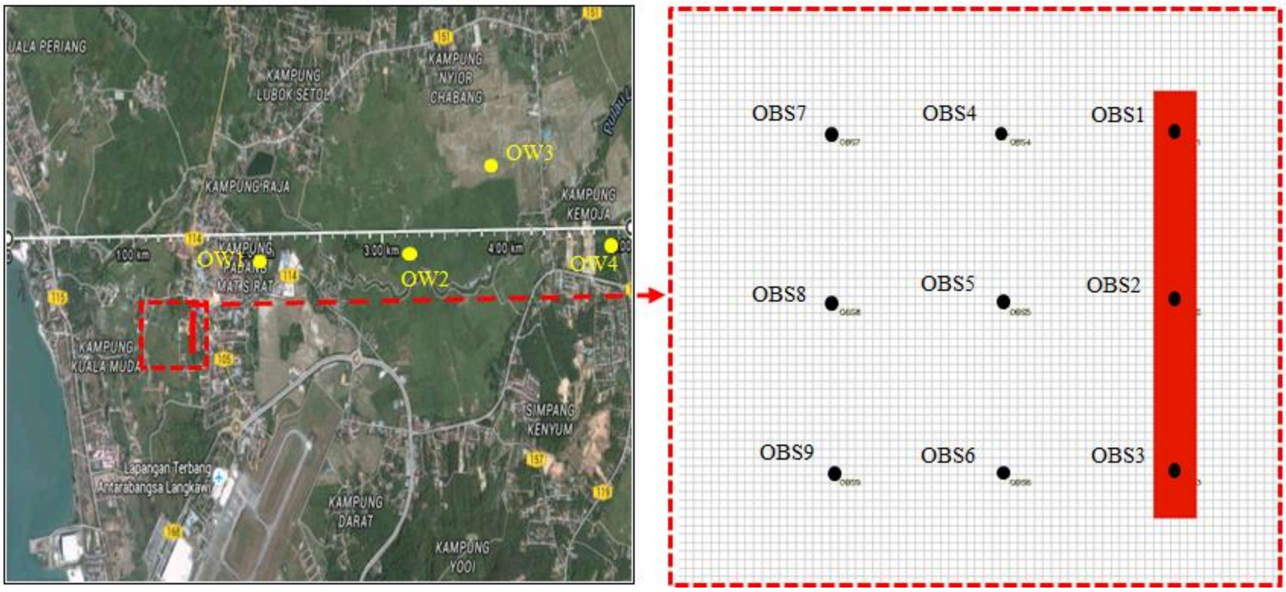


Figure 2. Study area for nutrient (pollutant) transport simulation in Kampung Kuala Muda [13]. The observation well OW1-4 used in calibration process is indicated in yellow. The nutrient release location on the paddy field is indicated in green. Nine observation wells (OBS 1-9) were simulated at 200 m interval

However in this study the nutrient (nitrate, NO_3) was applied as an instantaneous release of nutrient to examine the fate and transport of nutrient after application of fertilizer.

In Malaysia, two paddy planting seasons are implemented. The first season starts in April while the second season starts in September. In this study, two study cases were conducted using the groundwater level data in March and August 1995 as inland constant head boundary in Case 1 and Case 2 respectively. The first case represented the condition in dry season (low inland groundwater level) while the second case represented the condition in wet season (high inland groundwater level). The longitudinal dispersivity of contaminant was assumed as 10 m and the ratio of transverse to longitudinal dispersivity was taken as 1 in this study. Sorption of nitrate was neglected in the simulation as the nitrate is highly mobile with only little sorption on the solid matrix [14]. The molecular diffusion was also neglected in the simulation.

4. Transport Simulation Results and Discussion

The simulation results show that the expand and transport of nutrient plume in both study cases under short-term transport simulation (≤ 1 year) was not significant. The nutrient plume was dispersed approximately 100 m in width in both study cases after 12 months (Figure 3). Under the long-term simulation, the area of the plume due to dispersion in both cases has increased from approximately 180% to 600 % in 2, 5, 10, 20 and 30 years. The high flow condition (Case 2) has led to higher dispersion of plume compared with low flow condition (Case 1) in which the increment varied from 15.5% to 39.5% (Table 2, Figure 4). The transport distance of the plume from the released location has increased from 33.5 m after 2 years to 456.3 m after 30 years under low flow condition. Under high flow condition, the transport distance has further extended from 0.76 m to 72.1 m compared with the low flow condition in the simulation (Table 2, Figure 4).

In this study, the investigation was conducted to evaluate the fate and transport of the nutrient leaching into the aquifer system after fertilization process. Therefore, relative concentration (Resulting Concentration/Initial Concentration, C_t/C_0) is adopted in the analysis to demonstrate the change of concentration in the study area instead of using the simulated concentration as this could provide better understanding of the behaviour of the change of concentration of contaminant in the study.

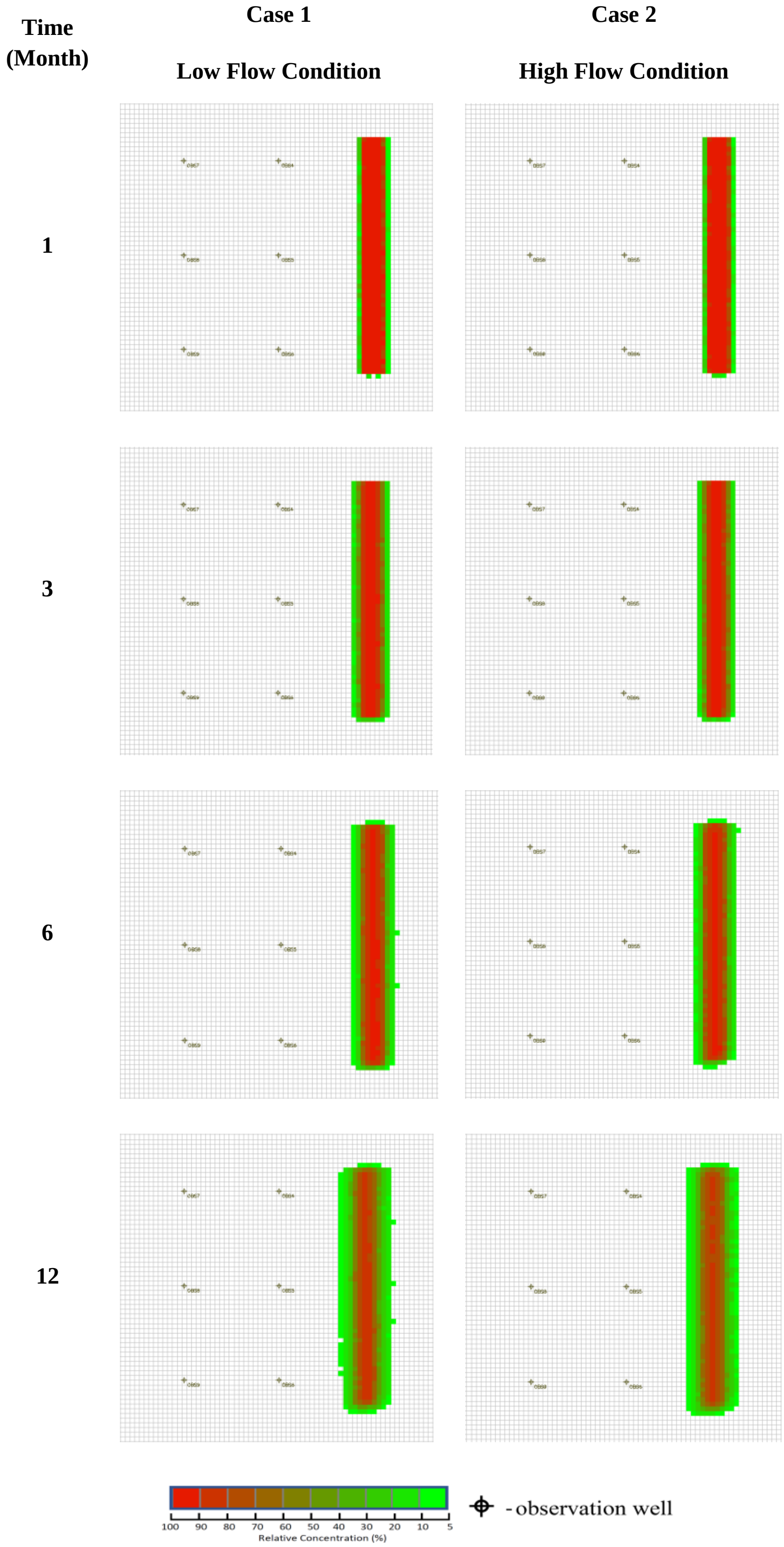


Figure 3. Nutrient transport prediction at 1st, 3rd, 6th and 12th month under short-term simulation. The plume showed the extent of relative concentration of nutrient to a minimum of 5%.

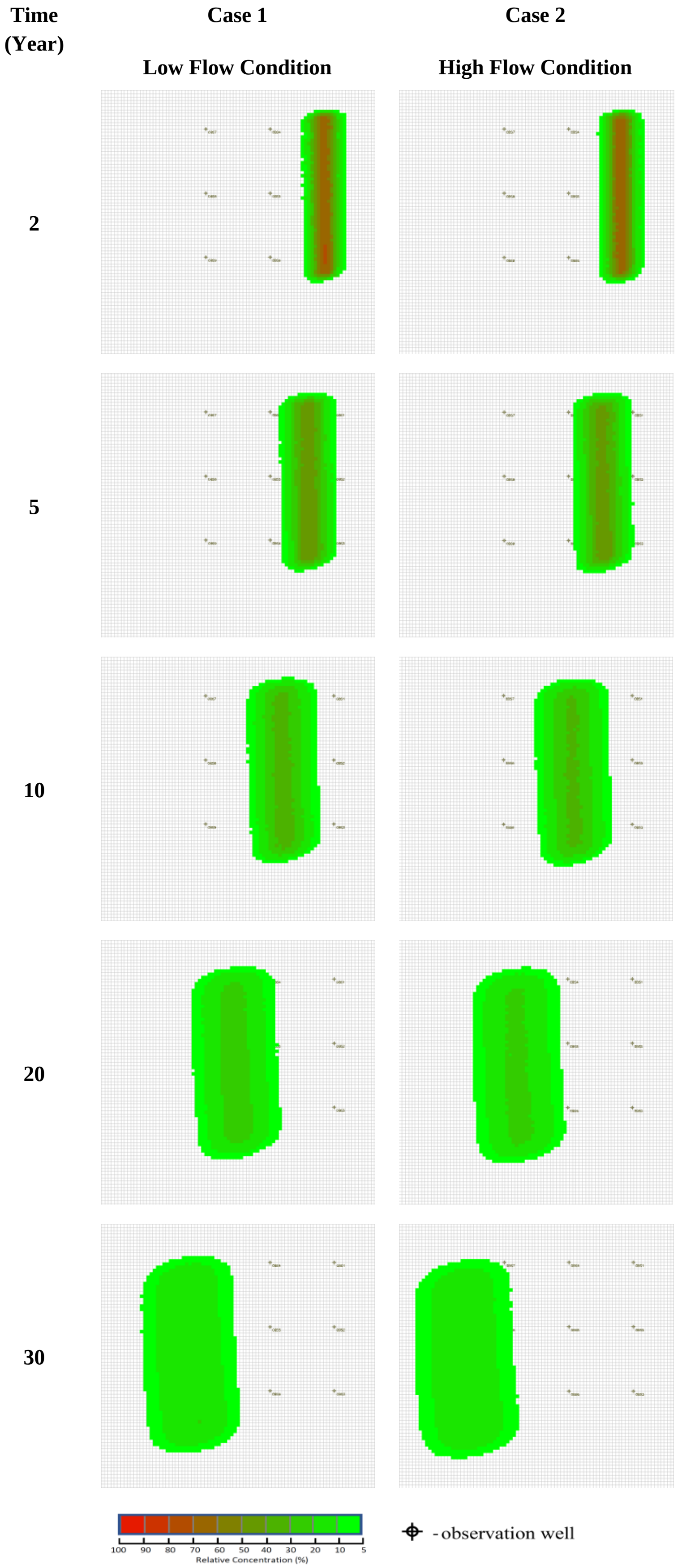


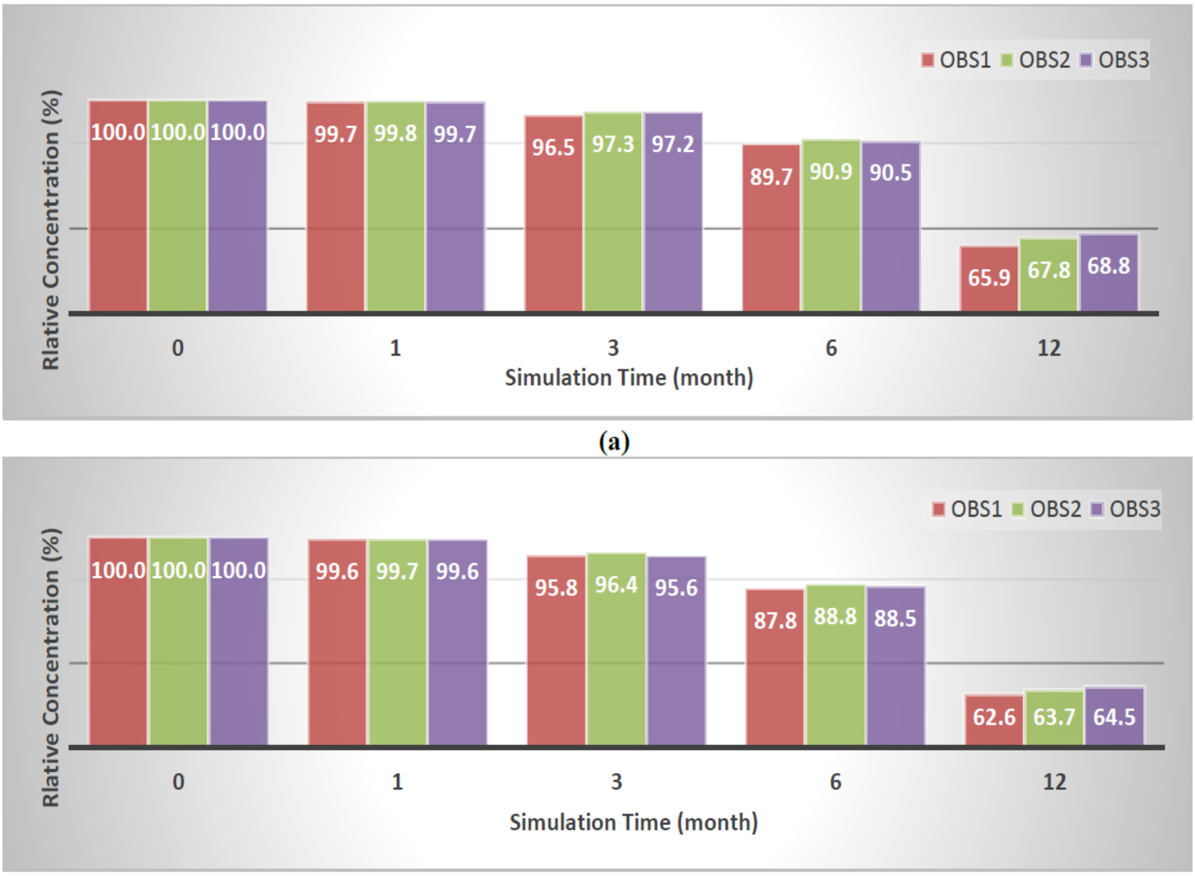
Figure 4. Nutrient transport prediction at 2nd, 5th, 10th, 20th and 30th year under long term simulation. The plume showed the extent of relative concentration of nutrient to a minimum of 5%.

Table 2. Results of plume dispersion and transport under long term simulation

Simulation Period (years)	Plume Area					Transport Distance[#]		
	Case 1* (m^2)	Case 2* (m^2)	Dispersion of plume (%)		Difference (%)	Case 1 (m)	Case 2 (m)	Difference (m)
			Case 1	Case 2				
2	70243	74108	181	196	15	33.5	34.3	0.8
5	92715	97403	271	290	19	81.4	93.9	12.5
10	119437	126017	378	404	26	162.7	187.7	25.0
20	147316	154902	489	520	31	313.6	362.3	48.7
30	164099	173965	556	596	40	456.3	528.4	72.1

[#] The transport distance was determined from the centroid of the plume.

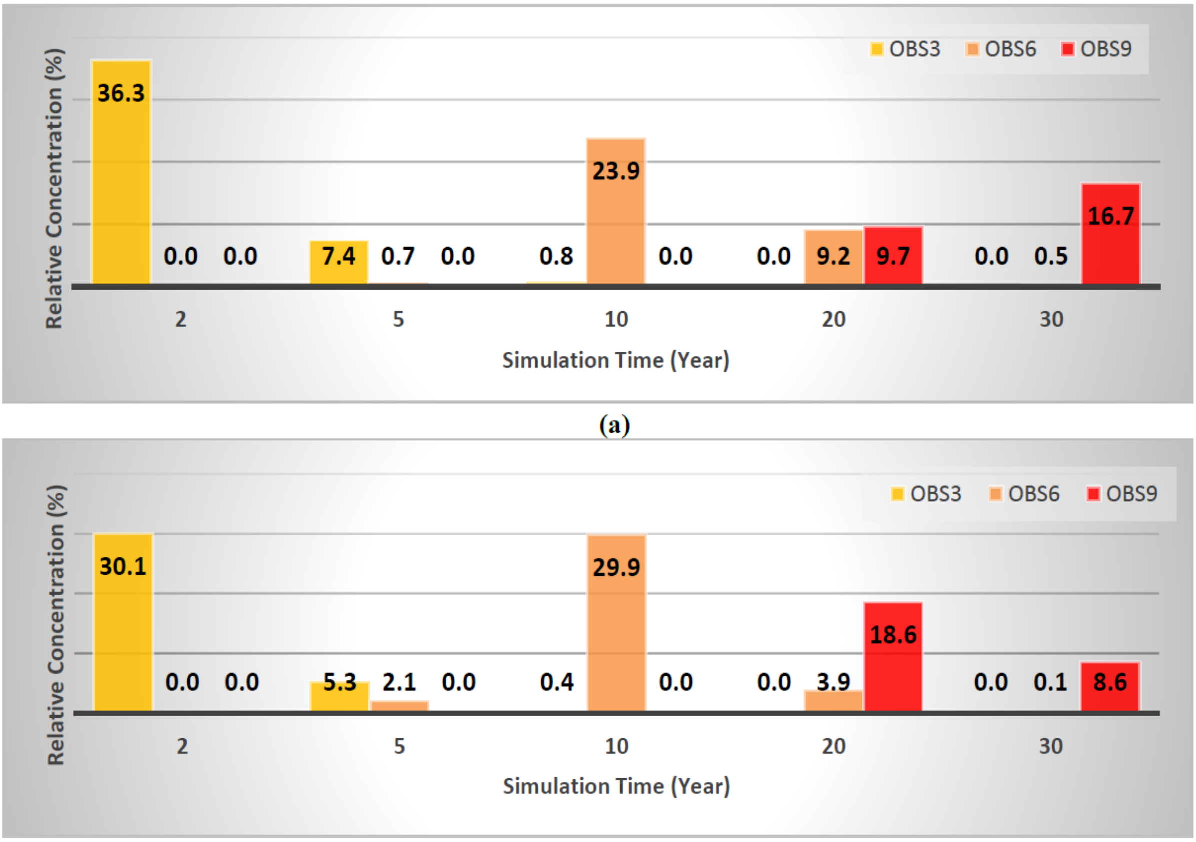
*Case 1 – low flow condition; Case 2 – high flow condition.



(a)

(b)

Figure 5. Relative Concentration in Observation Wells 1, 2 and 3 (a) Case 1 low flow condition and (b) high flow condition under short term simulation.



(a)

(b)

Figure 6. Relative Concentration in Observation Wells 3, 6 and 9 (a) Case 1 low flow condition and (b) high flow condition under long term simulation

Under short-term transport simulation, the relative concentration in observation wells (OBS) 1, 2 and 3 (the nutrient release location) was close to the initial concentration in study cases 1 and 2 (Figures 3 and 5) in the first three month under short term simulation (< 1 year). The reduction of nutrient concentration of nutrient was more significant after six months in the observation wells 1-3. After 12 months, the average reduction of nutrient concentration has increased to 32.5% and 36.5% under low flow and high low conditions respectively (Figure 5). The contaminant was nearly untraceable at the release location after 10 years (OBS 3 in Figure 6) in both study cases. The nutrient plume has reached the OBS 6 after 10 years which was located 200 m from the release location (Table 2 and Figure 6). The plume has further approached to OBS 9 located 400 m approximately 30 years under low flow condition. The travel time for the plume to reach OBS 9 was shorter under low flow condition which was at approximately 20 years (Table 2 and Figure 6). After 30 years, the concentration of nutrient was remained as 16.7% and 8.6% in Cases 1 and 2 respectively in the aquifer system.

In an agricultural practice, fertilizer is applied regularly throughout the cultivation process of paddy. However, the investigation was conducted by simulating an instantaneous fertilization process, and the results indicated that in each fertilization application cycle, the nutrient leaching into the aquifer system has remained at its release location in the first 6 months in the first month. The simulation results showed that the concentration of nutrient has taken approximately 5 years to reduce to less than 10% of the initial concentration. In the long-term simulation, the results showed that the nutrient was still detectable despite the concentration has been reduced to 16.8 % and 8.6% after 30 years (OBS9 in Figure 6).

5. Conclusions

In this study, a nutrient transport model based on a calibrated steady state flow model was developed to investigate the impact of fertilization on the groundwater contamination under dry and wet seasons. The results showed that the simulated plume has travelled approximately 456.3 m and 528.4 m seaward under low flow and high flow conditions respectively after 30 years. The simulation results showed that the concentration of nutrient was close to its initial concentration in the first 6 months at the release location. After 30 years, the concentration of nutrient plume has still remained as 16.7% and 8.6% under the low flow and high flow conditions respectively in the aquifer. As the fertilizer is applied regularly throughout the cultivation process in common practice, the findings of this study suggest that the best practice of controlling the groundwater contamination is to optimize the fertilization rate so that the cumulative effect of nitrate leaching into the groundwater system can be minimized. The simulation results could be used by the land use planners and environmental regulators in managing and utilization of water resources involving agricultural activities and protecting groundwater resources.

In this study, the model was developed using limited data. However, the model has been calibrated under steady flow condition, the transport model parameters were assumed in the simulation. For future study, it is recommended that the aquifer should be further calibrated and validated with the updated hydrogeological data especially the pumping test data and water quality data, to better estimate the model parameters such as hydraulic conductivity and solute transport parameters.

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