Journal of Groundwater Science and Engineering Vol.5 No.1 Mar. 2017

Climate change and groundwater resources in Mekong Delta, Vietnam

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Abstract: Groundwater resources have considerable influences on the human population and socioeconomic development of Vietnam and the Mekong River Delta (MRD). This paper presents an overview of the relationship between climate change and groundwater in the MRD, including the challenges, strategies and technical measures. Our results showed that groundwater levels are related to other climate and hydrological variables (*i.e.*, rainfall, river levels, *etc.*); therefore, the impacts of climate change on the groundwater resources of the Mekong delta are significant, especially on groundwater recharge. Based on the results of this study, it is recommended that groundwater development in the future should focus on reducing groundwater harvesting, enhancing groundwater quantity by establishing artificial works and exploiting surface water. This study suggests that the Artificial Neural Network (ANN) model is an effective tool for forecasting groundwater levels in periods of 1 month and 3 months for aquifers in the natural and tidal regime areas of the delta.

Keywords: Groundwater management; Climate change; ANN model; Mekong River Delta

1 Introduction

1.1 Status of groundwater

Groundwater resources have considerable influences on the human population and socio-economic development of Vietnam, particularly in the Mekong River Delta (MRD) region; however, few studies have focused on the trends in the impacts of climate change on groundwater resources. Scientists believe that climate change will have the greatest effect on water resources, agriculture, food security, community health and coastal zones. These issues require both short-term and long-term solutions to improve the planning and management of groundwater resources with regard to future climate change scenarios. The main objective of this study is to provide information on groundwater exploitation and suggest strategies to improve the management of this valuable resource under the threat of climate change.

The MRD has eight aquifers (Holocene (qh); Upper Pleistocene (qp_3); Upper-Middle Pleistocene ($qp_{2\text{-}3}$); Lower Pleistocene (qp_1); Middle Pliocene (n_2^2); Lower Pliocene (n_2^1); Upper Miocene (n_1^3); Upper-Middle Miocene ($n_1^{2\text{-}3}$) and Bazan Kanoizoi and Paleozoic–Mesozoic, which are two fissure and fissure-pore aquifers. Generally, the aquifer system in the MRD has an artesian basin structure and the lithology of each aquifer consists of fine to coarse sand, gravel, and pebbles. The deepest area of the basement is located below the Tien and Hau Rivers and rises to the NE, N and NW borders.

The characteristics of the aquifers in the MRD are summarized in Table 1. Approximately 2 million wells supply groundwater more than 2.8 million m^3/day, thus, groundwater is important for the socioeconomic development of South Vietnam.

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1.2 Predicted climate change scenarios

In 2012, the Vietnam Ministry of Natural Resources and Environment (MONRE) projected climate change and sea level rise scenarios for Vietnam according to low (B1), average (B2) and high (A2) carbon dioxide emission scenarios. These carbon dioxide emission scenarios are described as follows.

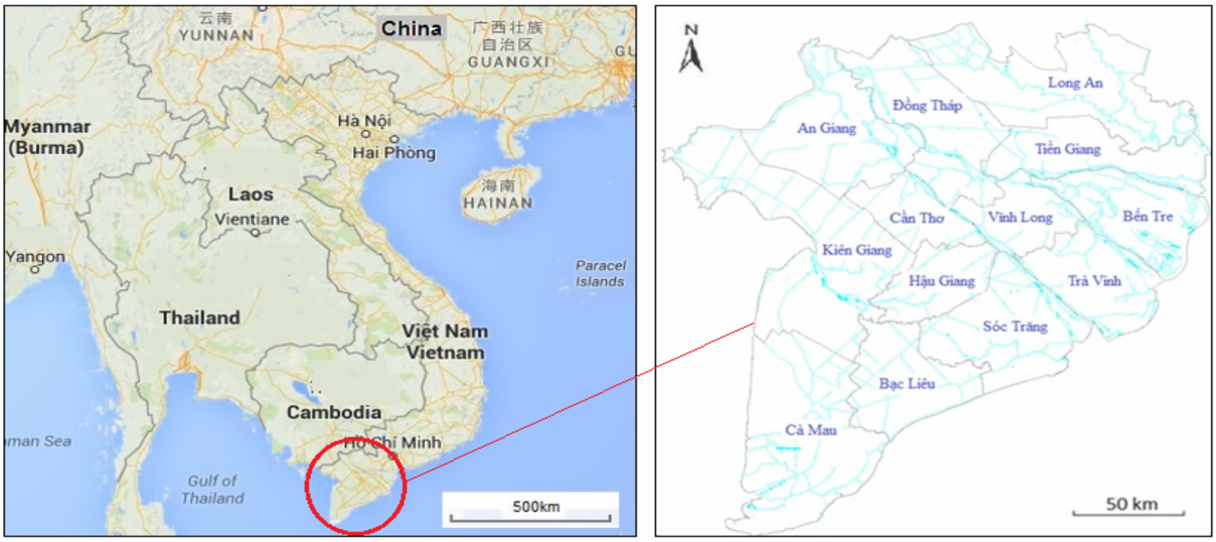


Fig. 1 Location map of the MRD (Google Earth and Vuong B T, 2014)

Table 1 Characteristics of the main aquifers in the MRD

Aquifers	Distribution	Thickness (m)	Depth (m)	Materials	Types	Groundwater potential	Groundwater quality
Holocene (qh)	40.000 km	15.5	16.9	Fine	Non-pressure	Poor	Low quality
Upper Pleistocene (qp_3)	Broadly distributed over the area	29.1	47.9	Silty clay, clay, sand, gravels	Low pressure	From poor to average, suitable for residential exploitation	Mainly salty
Upper-Middle Pleistocene (qp_{2-3})	Broadly distributed over the area	41.5	86.8	Silty clay, clay, sand, gravels	Low pressure	High potential, suitable for small-scale pumpings	Good quality
Lower Pleistocene (qp_1)	Broadly distributed over the area	38.1	146.5	Silty clay, clay, sand, pebble, gravels	Average pressure	From average to high	Good quality
Middle Pliocene (n_2^2)	Broadly distributed over the area	51.3	206.5	Courtyard mixed sand, clay-silty sand	High pressure	Rich groundwater potential	Good quality
Lower Pliocene (n_2^1)	Broadly distributed over the area	53.78	274.8	Courtyard mixed sand, clay-silty sand	High pressure	Poor to rich groundwater potential	Good quality
Bazan Kanoizoi		80		bazan olivin	Non or local pressure	Poor to average potential groundwater	
Paleozoic-Mesozoic	NW		4		Local pressure		

Table 2 Current groundwater exploitation in 13 local provinces in the MRD

No.		Province / Aquifer	An Giang	Bac Lieu	Ben Tre	Ca Mau	Can Tho	Đong Thap	Hau Giang	Kien Giang	Long An	Soc Trang	Tien Giang	Tra Vinh	Vinh Long
Total		Number of wells	6 374	93 368	2 653	67 328	48 798	4 838	40 572	93 130	3 435	80 069	1 530	88 833	22 207
		Q(m^3/ng)	94 537	248 728	17 986	159 118	188 844	116 169	62 544	197 441	195 554	244 850	140 664	224 773	32 473
1	qh	SL(well)	302	0	1 873	0	0	0	0	422	0	804	0	4 471	0
		Q(m^3/ng)	8 911	0	2 059	0	0	0	0	414	0	1 869	0	4 598	0
2	qp_3	SL(well)	4 517	12	548	0	0	0	9 821	18 283	0	11 051	0	0	0
		Q(m^3/ng)	41 673	106	1 926	0	0	0	11 982	34 018	0	25 240	0	0	0
3	$qp_{2\text{-}3}$	SL(well)	877	74 644	204	16 135	48 693	3 657	28 638	72 297	0	65 311	0	84 362	22 191
		Q(m^3/ng)	8 856	174 319	541	24 895	146 872	1 426	43 234	149 032	0	189 241	0	220 175	18 923
4	qp_1	SL(well)	0	18 688	0	8 535	0	0	2 113	2 090	26	2 814	0	0	0
		Q(m^3/ng)	0	61 838	0	28 592	0	0	7 328	3 642	11 491	17 186	0	0	0
5	n_2^2	SL(well)	662	24	0	42 353	105	1 181	0	35	1 998	4	310	0	0
		Q(m^3/ng)	34 185	12 465	0	105 198	41 972	114 743	0	6 835	144 585	0	17 376	0	0
6	n_2^1	SL(well)	2	0	23	304	0	0	0	3	1 356	0	378	0	16
		Q(m^3/ng)	864	0	10 161	433	0	0	0	3 500	35 609	0	23 536	0	13 550
7	n_1^3	SL(well)	0	0	5	0	0	0	0	0	54	85	842	0	0
		Q(m^3/ng)	0	0	3 300	0	0	0	0	0	3 869	11 314	99 752	0	0
8	ms	SL(well)	14	0	0	0	0	0	0	0	0	0	0	0	0
		Q(m^3/day)	48	0	0	0	0	0	0	0	0	0	0	0	0

Note: SL: Number of wells; Q: Exploitation flow

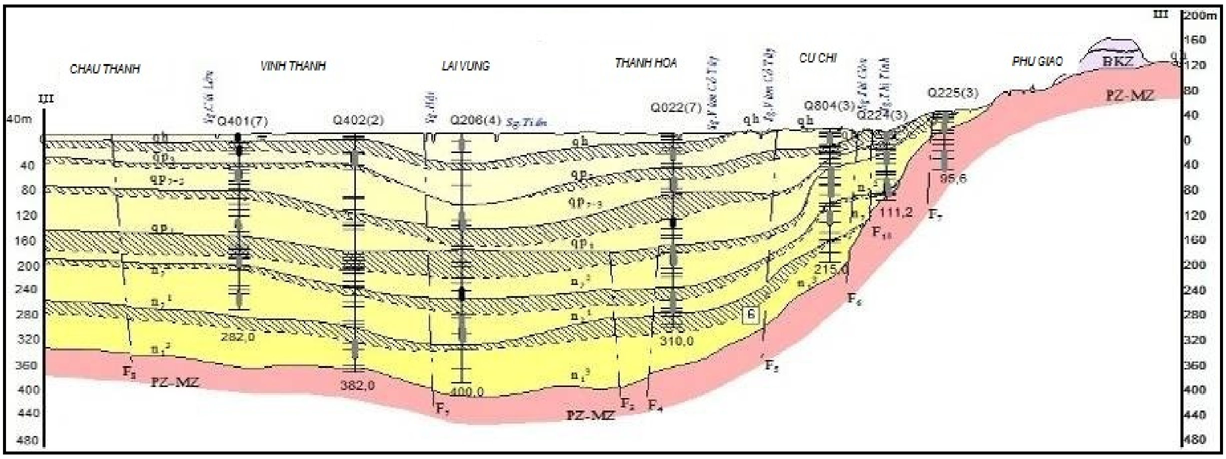


Fig. 2 Typical hydrogeological cross-section of the Nam Bo Basin from Tuyen Chau Thanh (Kien Giang) to Phu Giao (Binh Duong)

The projected temperature scenarios are as follows:

-B_1 scenario: In the dry seasons, the average temperature is projected to increase by 0.9-1.2 °C (by 2050); and 1.0-1.7 °C (by 2100). In rainy seasons, average temperature is projected to increase by 1.1-1.5 °C (by 2050); and 1.5-2.0 °C (by 2100).

-B_2 scenario: In the dry seasons, the average temperature is projected to increase by 0.8-1.3 °C (by 2050); and 1.5-2.0 °C (by 2100). In the rainy seasons, the average temperature is projected to increase by 1.2-1.6 °C (by 2050); and 2.5-3.8 °C (by 2100).

-A_2 scenario: In the dry seasons, the average temperature is projected to increase by 0.9-1.4 °C (by 2050); and 1.9 to 3.3 °C (by 2100). In the rainy seasons, average temperature is projected to increase by 1.2-1.6 °C (by 2050); and 2.5-3.8 °C (by 2100).

The projected precipitation scenarios are as follows:

-B_1 scenario: The rainfall in the dry seasons will decrease by 2.1-7.1% (by 2050) and 2.8-9.9% (by 2100). The rainfall in the rainy seasons will increase by 1.4-7.7% (by 2050) and 1.9-10.5% (by 2100).

-B_2 scenario: The rainfall in the dry seasons is projected to decrease by 2.3-7.8% (by 2050) and 4.3-15.1% (by 2100). The rainfall in the rainy seasons is projected to increase by 1.5-8.3% (by 2050) and 3.0-15.9% (by 2100).

-A_2 scenario: The rainfall in the dry seasons will decrease by 2.4-8.3% (by 2050) and 5.5-19.3% (by 2100). The rainfall in the rainy seasons is projected to increase by 1.6-8.8% (by 2050) and 3.7-20.2% (by 2100).

The projected sea level rise scenarios are as follows:

-B_1 scenario: In the east, the sea level will rise between 22 and 26 cm (by 2050) and 51-66 cm (by 2100). In the west, the sea level will rise between 24 and 28 cm (by 2050) and 52-72 cm (by 2100).

-B_2 scenario: In the east, the sea level will rise between 23 and 27 cm (by 2050) and 59-75 cm (by 2100). In the west, the sea level will rise between 25 and 30 cm (by 2050) and 62-82 cm (by 2100).

-A_2 scenario: In the east, the sea level will rise between 26 and 30 cm (by 2050) and 79-99 cm (by 2100). In the west, the sea level will rise between 28 and 32 cm (by 2050) and 85-105 cm (by 2100).

2 Climate change and groundwater sustainability

2.1 Climate change and hydrologic variability

2.1.1 Rainfall

The southern delta of Vietnam experiences rainfall ranging from 1 400 mm to 2 200 mm. Rainfall tends to increase gradually from a northeast to southwest direction. The amount of rainfall is <1 500 mm in the upstream area of the Cai Be and Go Cong Dong rivers and increases to >2 400 mm in Ca Mau Province. The annual average rainfall is approximately 1 800 mm. Higher average rainfall occurs in the upper and middle of the Dong Nai, La Nga and Be rivers (2 400-2 800 mm), the west coast region of the Mekong Delta (2 200-2 400 mm), the downstream of the Dong Nai River and the upstream of the Saigon River (2 000-2 200 mm). The lower average rainfalls occurs in the downstream of the Vam Co River and left bank area of the Tien River (<1 600 mm). The highest amount of rainfall occurs from August to October and ranges from 200-300 mm per month. The lowest amount of rainfall occurs in the period from January to March, which usually experiences no rainfall or negligible rainfall.

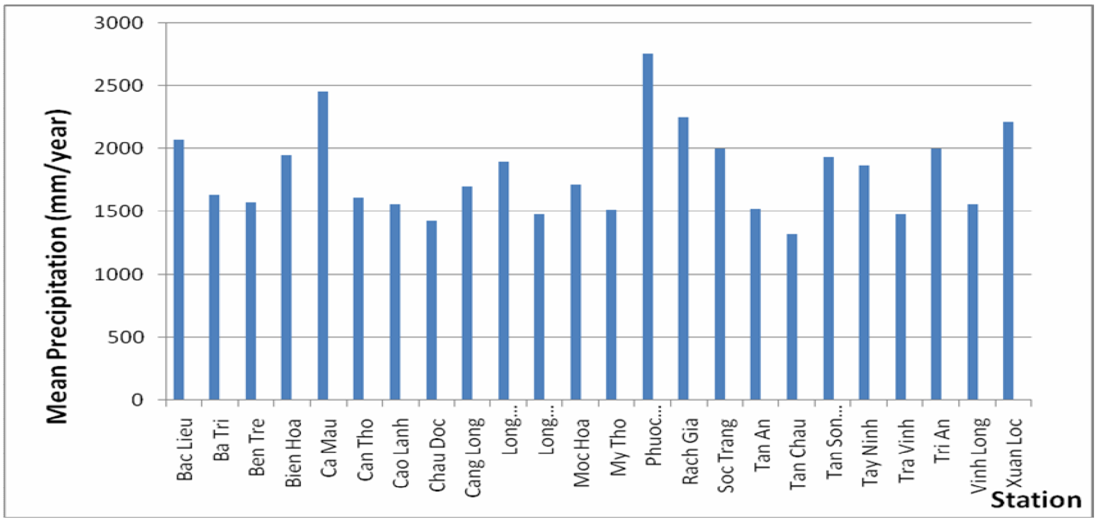


Fig. 3 Average rainfall at the meteorological stations in the Mekong Delta

2.1.2 Temperature

The average temperature in the region varies spatially and temporally and ranges from 25 to 29°C. High temperatures usually occur from April to May and commonly range from 28 to 30°C, and low temperatures typically occur from December to January and range from 24 to 25°C. The lowest temperature rarely occurs below 20°C and at the highest temperatures rarely exceeds 38°C. There is a vast difference of temperature between the day and night in a range of 8 to 10°C. The average monthly temperature does not vary much during the year and ranges from 3 to 4°C

In general, the high temperature and abundant sunshine lead to considerable evaporation in the entire region, with average values of 1 082 mm/year. Evaporation tends to increase in the Rach Gia coastal area and southeast region and ranges from 1 109 to 1 344 mm/year. In addition, in the Tra Vinh coastal area, evaporation is relatively low and only ranges from 809 to 841 mm/year. A large difference in evaporation is observed between the rainy and dry season, which ranges from 59 to 101 mm/month in the dry season and 48 to 69 mm/month in the rainy season. The highest evaporation occurs in March, and the lowest evaporation occurs in October.

2.1.3 Evaporation

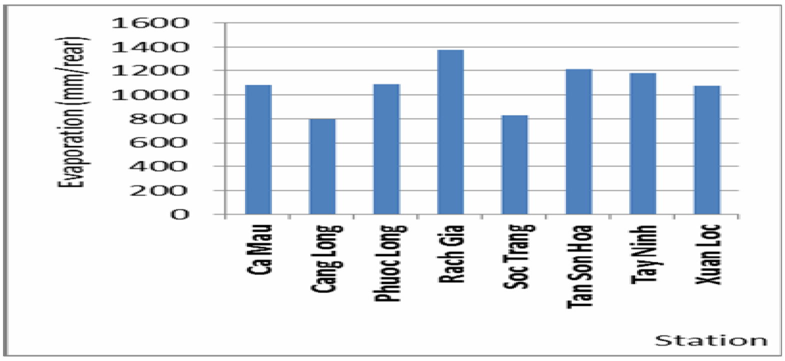


Fig. 4 Evaporation at the meteorological stations in the southern region

2.1.4 Hydrological regime

The hydrological system in the Mekong River Delta includes natural and artificial channels. The natural rivers include the Tien, Hau, Vam Co, Cai Lon and Cai Be. The artificial channel systems in the Mekong River Delta consist of three levels, including channel level 1 (main channel), channel level 2 and channel level 3 (field channel). The compound channel levels form a dense channel system at a density of 8-10 m/ha and a total length of 30 000-40 000 km throughout the MRD (Mekong Delta water resources assessment studies, 2011).

The hydrological regime on the rivers in the region formed the following two distinct seasons:

-Flood season (from June to November): The flood regime of the Tien and Hau rivers has a strong impact on the inland waterways. The strong rainfalls during the flood season cause flooding in the field areas. At the end of 2009, the water levels of the Tien and Hau rivers measured at two stations of My Thuan and Can Tho reached approximately 2 m; in the field in Vinh Long Province, the water level of the rivers and ditches reached the highest value for many years of observations at levels from 1.75 to 1.78 m.

-Dry season (from December to May): The hydrological regime of the dry season is dependent on the tidal regime of the South China Sea.

2.1.5 Tidal

The MRD is bounded by the South China Sea to the southeast and the Gulf of Thailand to the west (West Sea). The tidal regime has a strong impact on the study area. The tidal regimes in the East Sea and West Sea vary considerably and result in complicated groundwater system responses to tidal change. In the coastal rivers, the water levels in the Mekong and Dong Nai rivers fluctuate with the tide. In periods of low water levels (from April to June), the tidal oscillation amplitude is usually the largest. The observed tidal amplitude oscillations in certain hydrological stations in late May 2005 were 0.42 m at the Vam Co Tay River in the Moc Hoa district and 3.79 m at the Vung Tau Sea.

There is a large difference in tidal propagation between the southeast and the southwest. The tidal propagation in the downstream of the Dong Nai–Saigon River system shows a strong influence on the downstream of the Dong Nai–Saigon River, especially in the Saigon and Vam Co rivers. In the Dong Nai River, the tide has an influence on the watercourse until the Tri An waterfall over a distance of 100 km from the sea. The water level at Thu Dau Mot station in the Saigon River still shows a large influence of tidal fluctuations.

Tidal propagation in the MRD decreases inland, wherein the higher discharge source contributes to faster decreases in tidal fluctuations. During large floods of the Mekong, the tide is off Tan Chau or Chau Doc, whereas during the dry season when the discharge source is approximately 2 000 m^3/s, the tidal amplitude at Tan Chau may reach above 1.0 m and could reach 0.40 m at Phnom Penh, which is at a distance of over 300 km from the sea.

2.2 Impacts of climate change on groundwater

2.2.1 Interaction of groundwater, climate and hydrologic variables

The major meteorological-hydrological factors that influence the groundwater system of the MRD can be divided into the following three categories: (1) Meteorological model, (2) Hydrological model, (3) Tide model.

Water level fluctuations because of meteorological factors:

Rainfall is the major factor leading to seasonal fluctuations of the groundwater level. During the wet season, rainwater usually replenishes aquifers, whereas during the dry season, especially in the months without rainfall, groundwater levels decrease. In the MRD, water levels tend to rise starting in May because of the increased rainfall events at the beginning of the rainy season.

Fig. 5 shows that water level variations and rainfall are strongly correlated, with increased rainfall intensity leading to steeper water level rises. Groundwater level fluctuations follow the timing of rainfall from 1 to 3 months. During the dry season, the water level decreases and reaches a minimum at the end of the season. When the rainy season starts, the water level rises gradually from May and reaches its maximum at approximately November. Meteorological factors influence the groundwater in shallow aquifers. The water level fluctuation range depends on the terrain and groundwater depth. In the Holocene layer, the amplitude does not exceed 4 m and generally ranges between 1.0 and 2.5 m, whereas in the basalt layer, the amplitude ranges from 6.0 to 10.0 m and even reaches 16.0 m.

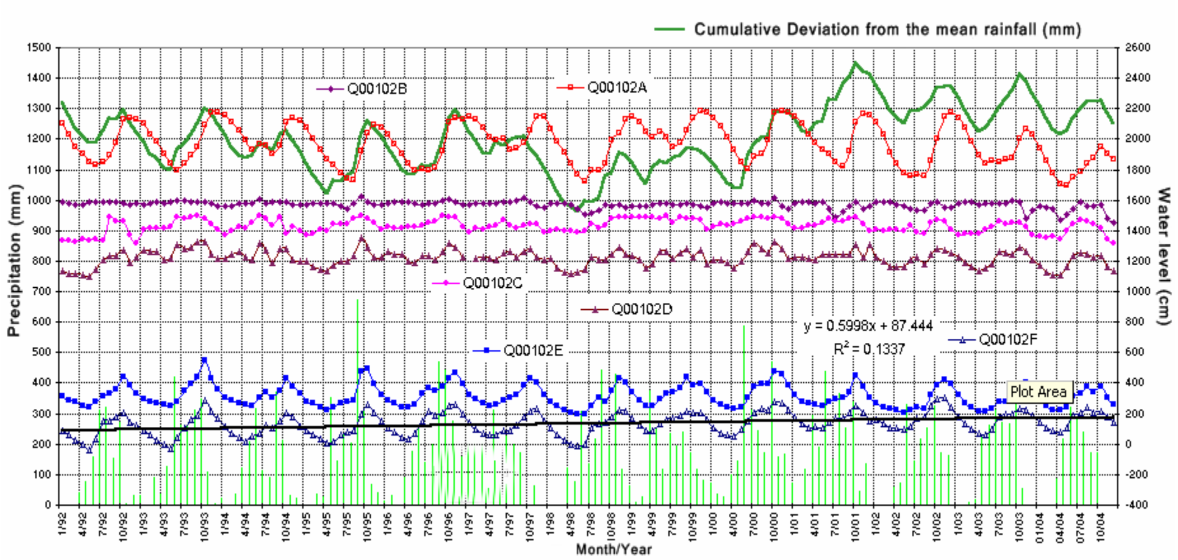


Fig. 5 Relationship between the water level and rainfall line in Duong Minh–Tay Ninh

Water level fluctuations caused by hydrological factors:

The groundwater level is mainly influenced by hydrological factors of rivers, which can be observed along the major rivers, such as Dong Nai and Saigon. The maximum and minimum groundwater peaks coincide with the maxima and minima of river water levels. The groundwater level fluctuation line and the river level are consistent.

In the southern region, rivers and streams often have permeable bottom sediments connected with the aquifers, and this connection forms favorable conditions for the exchange of water between the surface water and groundwater. In the rainy season, groundwater will discharge and create a temporary flow to the surface water. The opposite occurs during the dry season, with the surface water providing water to the groundwater. Water exchange depends on the permeability of bottom sediments layer and the water level difference between groundwater and surface water. In many cases, groundwater and surface water in the MRD region show a robust relationship. Previous studies have observed that the correlation coefficient between river water and groundwater at station Q031 An Phong, Thanh Binh, Dong Thap ranges from 0.98 to 1.00 for the qh floor and from 0.87 to for the $qp_{2\text{-}3}$ and 0.92 for the qp1 aquifer.

Water level fluctuations caused by tidal factors:

Groundwater level fluctuations are also governed by fluctuations of the tidal level. In the southern delta region and certain specific regions of the western delta, tidal influences invade deep into the MRD delta and induce groundwater level fluctuations.

2.2.2 Impacts of climate change on groundwater

According to the latest research by the National Center for Water Resource Planning and Investigation (NAWAPI), the annual amount of groundwater recharge of the delta region will range from 1.7 to 3.5 million m^3/day for scenario B1, 1.4 to 3.4 million m^3/ day in scenario B2 and 1.0 to 3.5 million m^3/day for the A2 scenario. The amount of groundwater recharge for the rainy season is greater than that for the dry season. In all three scenarios, the groundwater recharge rates are projected to decrease over time. The average decreasing rates are 20.421, 23.708 and 28.050 m^3/day for scenarios B1, B2 and A2, respectively. A tendency of reduced groundwater recharge rates is observed in both the dry and rainy seasons, although the change in the amount of groundwater recharge varies spatially. The projected groundwater recharge rates for the period 2020-2100 under the climate change scenarios are illustrated in Fig. 6.

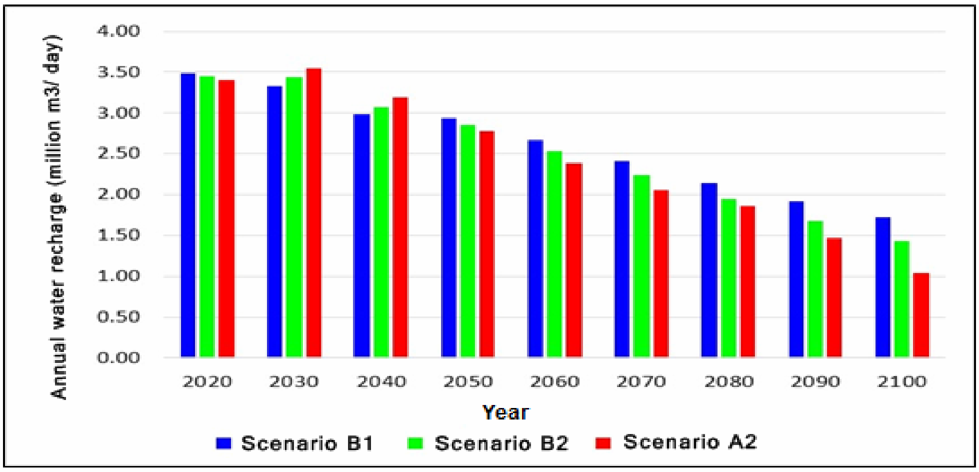
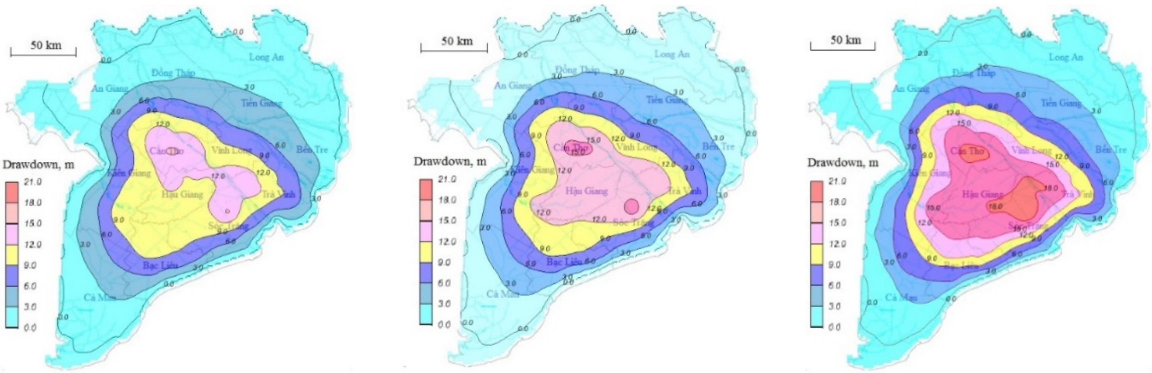


Fig. 6 Projected groundwater recharge rate in the MRD from 2020 to 2100 under different climate change scenarios (Vuong B T, 2014)

The indicators used to assess the impacts of climate change (CC) on groundwater resources are i) variations in groundwater level, ii) changes in the annual accumulated groundwater quantity, iii) variations in areas with total mineralization (M) greater than 1 g/l.

Fig. 7 presents the maps of the projected drawdown of groundwater level from 2010 to 2100 on the aquifer qp_{2-3} under different climate change scenarios. In the same aquifer, the water level rises tend to decline from the lower emission scenario (B1) to the higher emission scenario (A2).

The rate of water level decline and the rate at the center of the cone of depression within each aquifer are listed in detail in Table 3.



Scenario B1 Scenario B2 Scenario A2

Fig. 7 Lowering water level from 2010 to 2100 in the aquifer qp_{2-3} (Vuong B T, 2014)

Table 3 Lowering water level from 2010 to 2100 under different climate change scenarios (Vuong B T, 2014)

Aquifer	**Lowering water level**			**Rate of lowering water levels (m/yr)**		
	Scenario			**Scenario**		
	B1	B2	A2	B1	B2	A2
qp_3	8.1	8.5	10.3	0.1	0.1	0.1
qp_{2-3}	14.5	15.0	17.4	0.2	0.2	0.2
qp_1	4.9	5.5	4.8	0.1	0.1	0.1
n_2^2	37.3	39.1	44.5	0.4	0.4	0.5
n_2^1	1.6	1.5	1.5	0.0	0.0	0.0
n_1^3	20.5	20.7	22.4	0.2	0.2	0.2

Fig. 8 illustrates the changes of the annual accumulated groundwater quantity in the Mekong Delta under different climate change scenarios. The annual accumulated groundwater quantity shows a negative value (except in 2030 and 2040 of scenario A2), which means that in terms of quantity, the groundwater resources in the delta will continue to decline.

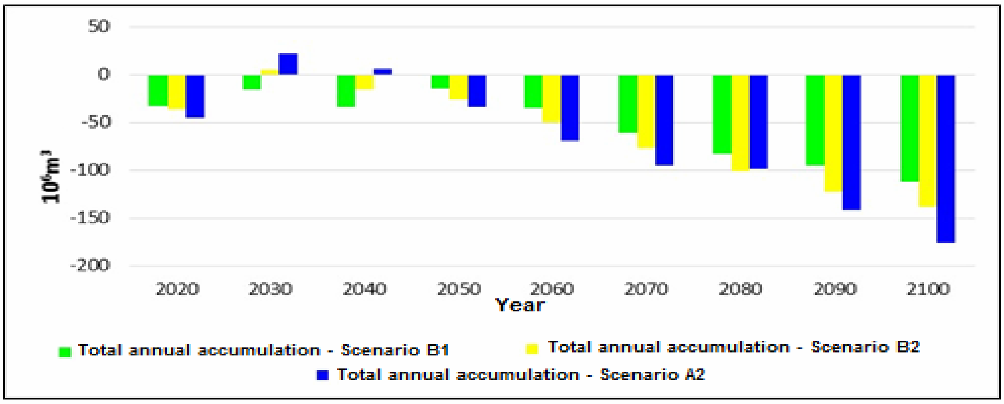


Fig. 8 Changes of the annual accumulated groundwater in the MRD from 2020 to 2100 under different climate change scenarios (Vuong B T, 2014)

Table 4 shows the changes in the area of saline groundwater in the MRD in 2100 compared with that in 2010. The total area of the saline groundwater region (groundwater mineralization region) is defined as the aquifers with salt concentrations greater than 1 000 mg/l. The results showed that the saline regions tend to increases in all aquifers except for aquifer qh. The growth rate of saline groundwater aquifer area is the largest for the A2 scenario and nearly the same with the B1 and B2 scenarios.

Table 4 Increasing area (km^2) of saline groundwater aquifers in the year 2100 compared with that in 2010 (Vuong B T, 2014)

Aquifer	qh	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3
Scenario B1	-1 214	753	5 389	4 033	1 471	1 695	2 637
Scenario B2	-1 064	771	5 407	4 051	1 472	1 694	2 638
Scenario A2	766	2 538	7 174	5 818	3 188	3 156	3 429

In all three climate change scenarios, both the groundwater levels and storage capacity are projected to decrease annually, whereas the area of saline groundwater increases with time. These tendencies are exacerbated under the high emissions scenario (A2), and such issues are primarily caused by reduced groundwater recharge.

3 Adaptation challenges and strategies

3.1 Challenges

To manage future climate changes in the MRD and Vietnam in particular, a good water management plan (policy) is required. Various challenges must be overcome, including social, economic, socioeconomic and water governance issues.

In Vietnam, rapid population growth and urbanization have exerted an increasing demand for water. The rising disparity in income has widened the access gap to the water supply and sanitation. Public awareness and education are important for educating local populations on water-related issues. The view that “water is endlessly given by God” has to be eradicated and the concept of water saving and protection must be understood by the masses. Regulations and law enforcement on littering in public spaces and waterways could be reviewed to prevent urban rivers from becoming rivers of “garbage”. Raising and changing public awareness and behaviors are thus essential to the sustainable conservation of water resources.

From an economic perspective, Vietnam's rapid economic development along with the shift from agriculture towards the industry and services sectors has caused a fundamental change in water usage. The management of water resources could be improved by the implementation of a user-pay and polluter-pay principle, the application of water market solutions, and the protection of weaker and poorer water users.

Improving water governance in Vietnam could be implemented via better cooperation and management of the related ministries, agencies and human resources. In the past, water resource management at national and trans-provincial levels was mainly the responsibility of the Ministry of Agriculture and Rural Development (MARD), whereas at the local level, it was performed by the Departments of Agriculture and Rural Development. Reforms to water resource laws in 2002 shifted the management responsibilities to the newly established Ministry of Natural Resources and Environment (MONRE) and provincial Departments of Natural Resources and Environment. MONRE's function is to oversee water resource management activities, whereas MARD's responsibility is to deliver water-related services. Despite these changes, human resources have not been managed accordingly, which has led to severe shortages of experts working in water management sectors. The personnel survey of MONRE in 2010 showed that the proportion of human resources for the water sector was only 0.4%, which is the lowest number of human resources in the natural resources and environment sectors.

In addition to the abovementioned challenges, the water governance in Vietnam also faces an inherent ecological constraint of water availability. With a total annual surface water availability of 3 480 m^3, Vietnam has been officially announced "a water deficient nation". Approximately two thirds of Vietnam's water resources originate outside the country; thus, Vietnam is susceptible to water resource decisions made in upstream countries. The uneven distribution of the average annual rainfall of 1 940 mm across Vietnam and the prolonged dry season result in serious water shortages in many areas. Vietnam has been featured as one of the most water disaster-prone countries in the world, and its different geographical regions differ in their level of water vulnerability. The coastal lowland regions with an increasing population density are becoming more vulnerable to impacts from global warming and deforestation, such as salinity intrusion and flooding, whereas the high mountain regions have experienced more serious droughts and flash floods.

3.2 Strategies to protect groundwater resources under the climate change scenarios

To overcome such multidimensional challenges related to water governance for the sustainable management of scarce water resources, a number of strategies and initiatives are being taken in Vietnam. Improving the legal framework and legal enforcement for the management and protection of water resources are among the highest priorities. International and regional cooperation to gain international support and assistance is also crucial to ensuring water security. A comprehensive database of national water resources is currently under development and will provide a resource for basic investigational data, monitoring data and water resources prediction data. Water resources planning, including the allocation and protection of water resources and the prevention of water-related damage, at the national, river basin and local levels and conflicts in water sharing are being resolved. Public education and awareness of sustainable water usage is being implemented. The consolidation of water institutions, improvement of institutional capacities and enhancement of public-private partnerships in water activities are being considered.

3.3 Technological measures to protect water resources under climate change scenarios

3.3.1. Establishment of groundwater monitoring networks

The southern region is one of the key economic regions of Vietnam. Along with surface water, groundwater plays a significant role in the economic activities and livelihoods of local populations, especially in the southwestern provinces. To protect the valuable water resources in the MRD region, research, exploitation and protection of water resources have been a focus in Vietnam. A water monitoring network for the southern region has been planned and operated since the 1990s and consists of the following main stages:

Network construction from 1990-1995

On December 12, 1988, the Directorate of Mines and Geology (currently the Department of Geology and Minerals of Vietnam) produced an important document, Document No. 1113 ĐC-KHKT (tasked to the Eighth Geology and Hydrology Union, currently the Union of Hydrogeological-Geological Construction for the South), which emphasized the management and protection of mineral resources. In June 1990, the plan for monitoring groundwater dynamics in the southern delta was approved by the Ministry of Industry. By 1995, the southern regional networks were built, which included 76 monitoring stations and 3 balance fields with 198 works, including 187 boreholes, 6 surface water monitoring projects, 3 rain gauge works and 2 arteries observation works.

Unified operations from 1996 -2000

The "National Comprehensive Groundwater Monitoring in Three Regions: North Delta, Southern Delta and Central Highlands" scheme approved by the Ministry of Industry via decision No. 3460 QĐ/CNCL dated 16th November 1996 and the decision No. 1435 QĐ/CNCL dated 29th June 1999 achieved the following results:

Identified the main types of groundwater movement across the southern delta and mapped the dynamics of the aquifers; performed ground-water monitoring for the period 1991-2000 to determine the water levels, temperature, and chemical composition. Identified the groundwater rules as well as the increasing and decreasing trends of water levels and chemical compositions of the aquifers.

Studied the conditions of underground water formation, assessed the quantity of water supplied from rainfall to groundwater and surface water, and identified the relationship between groundwater and aquifers.

Operational phase and additional planning

The period from 2001-2005 was the operational phase, and the primary objective was to establish dynamic zone maps for the 5 southern regional aquifers. Subsequently, the project "Upgrading the groundwater monitoring network in the Southern Region" was conducted upon approval of the "Master Plan for A Water Resource Monitoring Network and National Environment by 2020" according to decision 16/2007/QD-TTg dated 29 January 2007 and its implementation as approved in decision 1182/QD-BTNMT dated June 5th 2008.

The project led to the development of 7 monitoring points and 26 new works and renovations with 19 points and 31 works in the southern region, thus leading to 70 points with 220 monitoring projects. The new points are Long An with 3 points and Dong Thap (TP) City, An Giang and Tay Ninh with 1 point each.

NAWAPI reviewed the work and proposed adjustments to the network plan following decision 16/2007/QĐ-TTg. The network has been expanded to the large islands and includes sea water monitoring wells. The quantity and quality of the observed data have also been improved considerably.

Currently, the water resource monitoring network in the southern region of the MRD is mainly composed of groundwater monitoring works with 86 points and includes 220 works distributed in 17 out of 19 provinces and cities in southern region (except Tien Giang and Ba Ria-Vung Tau). The monitoring points are designed to form 5-line and 4-perpendicular line routes (along the Mekong River and Dong Nai), thereby covering most of the southern region. Based on the observed groundwater monitoring data, studies on the hydraulic relationship between surface water and groundwater in the MRD are being conducted.

3.3.2. Improving forecasts of climate change impacts on groundwater levels

In addition to groundwater monitoring, groundwater level predictions are an important requirement for groundwater planning and usage in all areas. Recent studies have shown that the Artificial Neural Network (ANN) model is a robust tool for resolving various water resource problems, including time-series forecasting (Yoon H *et al.* 2011). In an attempt to forecast future groundwater level responses to various hydrological factors, including climate change, the ANN model has been used to predict groundwater levels for the

Middle Pliocene aquifer (n_2^2) of the southern plain in the MRD. The input variables for the model are selected from rainfall data, groundwater levels, seawater levels and exploitation discharge by analyzing the correlation using SPSS software.

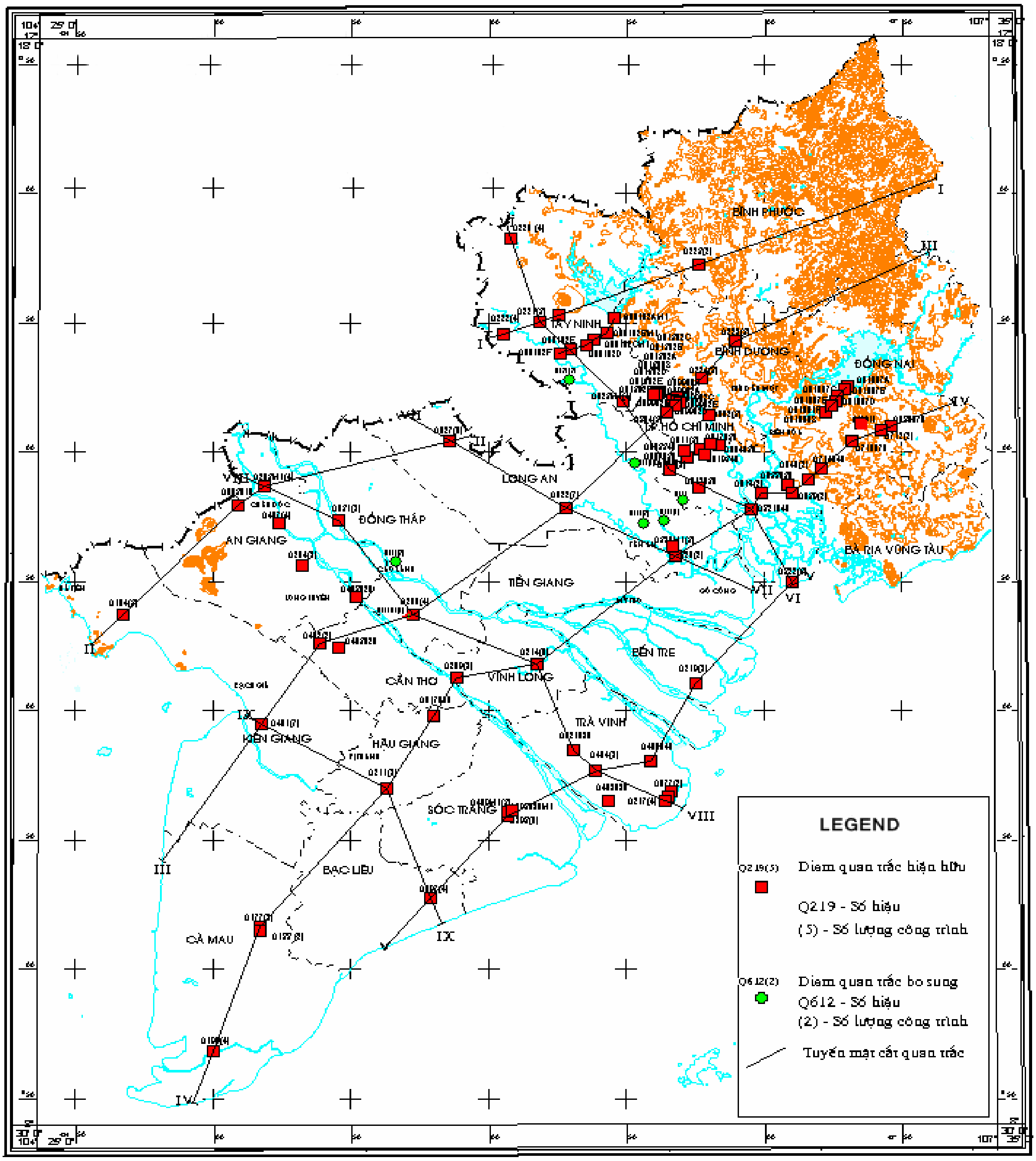


Fig. 9 Current GW monitoring network in the Mekong Delta (Source: NAWAPI)

The statistical norms of the model groundwater level predictions at 1 month to 3 months in the tidal and natural regimes of the Middle Pliocene aquifers (n_2^2) are summarized in Table 5.

The constructed ANN model for the model groundwater level predictions at 1 month to 3 months showed reasonable consistency and high accuracy for all of the statistical indicators during the calibration and validation process. For example, the RMSE (root mean square error) of the model was <0.1, which indicates that the model calibrations (and verifications) were successfully performed. In addition, these patterns showed high values with P>90%. These results indicate that the

ANN model is appropriate to predict groundwater levels in the different regime areas of the Middle Pliocene aquifer (n_2^2).

Fig. 10 and Fig. 11 show that the correlations between the observed and forecasted groundwater level in both the natural and tidal regime areas were good at $R^2 > 0.9$. This result indicates that the ANN model with the network structure and parameters defined above provides accurate forecast results and thus can be used to forecast the groundwater levels for natural and tidal regime areas of the Middle Pliocene aquifer (n_2^2) of the southern delta region with prediction times from 1 to 3 months.

Table 5 Calibration and validation parameters of the ANN model for the natural and tidal regime areas of Middle Pliocene aquifer (n_2^2) in the southern delta

Regime areas	Forecast times	Cases	Model Structure	Study parameter	Moment parameter	RMSE	Good pattern (%)
Natural	1 month	Calibration	17-12-1	0.1	0.5	0.04	100
		Validation		0.1	0.5	0.018	90
	3 months	Calibration	14-10-1	0.15	0.45	0.02	100
		Validation		0.15	0.45	0.01	95
Tidal	1 month	Calibration	12-9-1	0.2	0.5	0.04	100
		Validation		0.2	0.5	0.03	95.8
	3 months	Calibration	18-12-1	0.3	0.5	0.002	100
		Validation		0.3	0.5	0.009	93

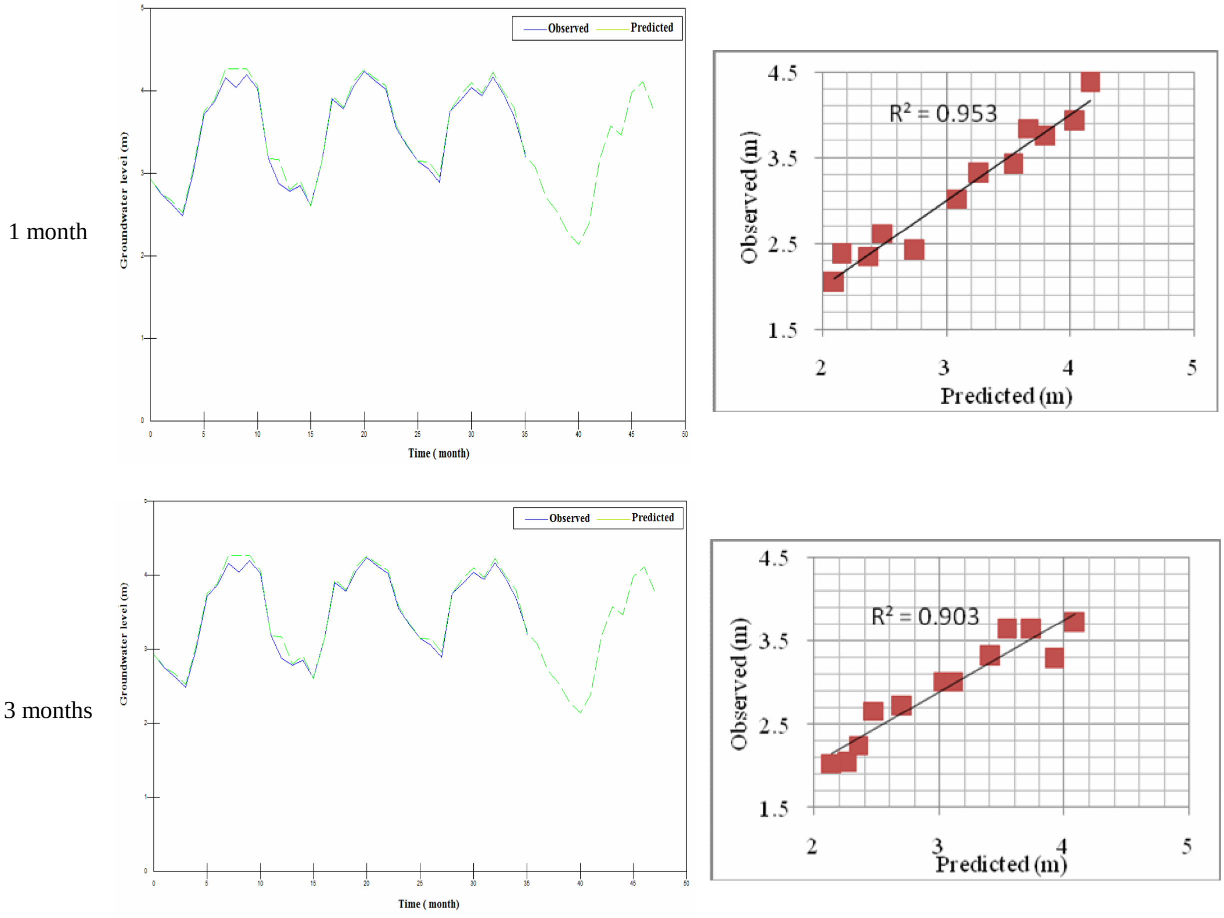


Fig. 10 Results of the groundwater level forecasts for 1 month and 3 month periods for natural regime areas in the Middle Pliocene aquifer (n_2^2)

4 Conclusions

The paper provides a comprehensive overview of the interactions between climate change and groundwater in the Mekong delta. The study shows that groundwater levels are correlated with climate and hydrological variables (*i.e.*, rainfall, river levels, *etc*.), and climate change has an especially significant impact on groundwater recharge in the Mekong Delta. The results illustrated that the impacts of groundwater exploitation and climate change on the groundwater resources in the Mekong Delta could be qualified by groundwater flow modelling and diffusion modelling. In addition, the results also indicate that the ANN model is an effective tool for forecasting groundwater levels over periods of 1 month and 3 months for the natural and tidal regime of the Pliocene aquifers of the delta. To develop effective adaption and management strategies for the groundwater in the Mekong Delta under climate change, a number of strategies, actions and technical measures must be enacted. Groundwater development in the future should focus on reducing groundwater harvesting, enhancing groundwater quality via additional artificial works, and exploiting surface water to a greater degree.

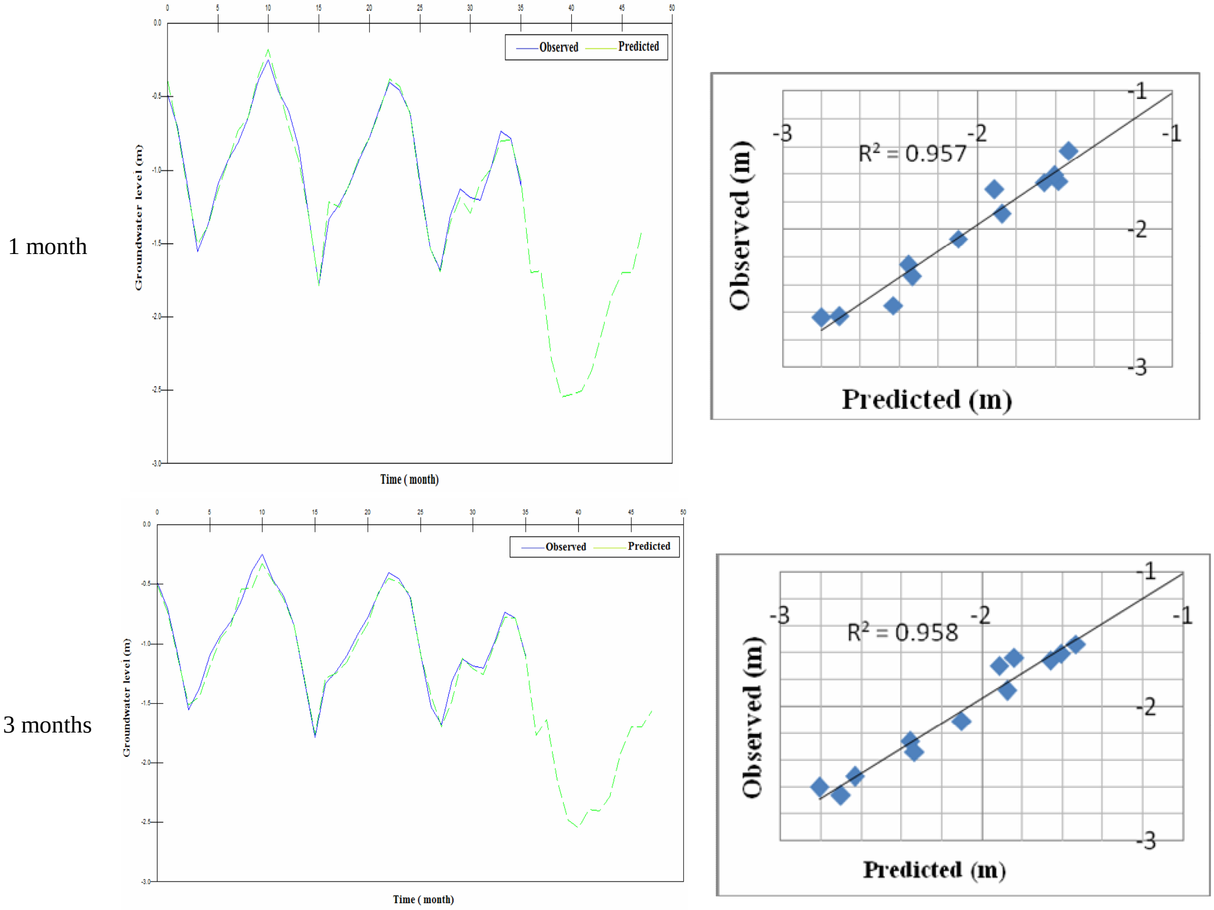


Fig. 11 Results of the groundwater level forecasts for 1 month and 3 month periods for the tidal regime area in the Middle Pliocene aquifer (n_2^2)

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