Estimation of groundwater use pattern and distribution in the coastal Mekong Delta, Vietnam via socio-economical survey and groundwater modeling

Tuan Pham Van[1,a*], Sucharit Koontanakulvong[1,b]

Tuan Pham Van
Department of Water Resources Engineering
Faculty of Engineering, Chulalongkorn University
Bangkok 10330, Thailand
Email: phamtuanld8@gmail.com

Sucharit Koontanakulvong
Department of Water Resources Engineering
Faculty of Engineering, Chulalongkorn University
Bangkok 10330, Thailand
Email: sucharit.k@chula.ac.th

Abstract: Surface water resources in the Mekong Delta are under increasing strain due to unplanned extraction, pollution, salinization and climate change effects. In many provinces of Mekong delta, excessive groundwater extraction has resulted in many serious groundwater-related problems. The increase in demands and the aforementioned negative effects of groundwater depletion raise the urgent question: at what time in future are the limits to local groundwater use reached? Hence, there is a need to know groundwater use (GWU) pattern and distribution in the study area for future groundwater management.

In this study, firstly, the study used socio-economic data of Tra Vinh Province to classify group of revenue, potential of water resources and population distributed in each district to design and conduct the socio-economic survey to explore information relevant to groundwater use (GWU) for each purpose. Secondly, the data set of 419 survey questionnaires per 9 survey communes were analyzed by SPSS tool to estimate ratio of household using groundwater (RHHUG) for each purpose as well as average pumping rate (APR) per household and per ha for domestic use agriculture use, respectively. Thirdly, the APRs were extended to propose the total groundwater use pattern and distribution during 2007-2016 by using socio-economic data of the province and expand to spatial distribution by using correlation with land surface temperature (LST) which was estimated from Landsat 8. Besides, the groundwater flow model of the study area was developed to verify and correct amount of groundwater pumping (pattern and distribution proposed) from 2007 to 2016.

The study found that the annual GWU of Tra Vinh Province in 2016 was 347,793 m^3/d in which both Duyen Hai district and Tra Cu district occupied more than 50 percentages, i.e., about 188,551 m^3/d. In those two districts, RHHUG increased from 2 to 3 times during the period of 2007 and 2016. LST distribution performed a good correlation (R^2 = 0.646) with GWU distribution in Tra Cu district. Results of groundwater modeling shown that the discharge from aquifer (mainly pumping) was always higher than the recharge to aquifer. It explained why the observed groundwater level declined about 0.1 m per year of the period from 2007 to 2016.

Keywords: groundwater use, pattern, distribution, groundwater modeling, land surface temperature, field survey

I. INTRODUCTION

Groundwater abstraction has increased rapidly and declining groundwater levels now pose an immediate threat to drinking water supplies, livelihoods in the Mekong Delta (IUCN 2011). In addition, groundwater resources sustain a significant and increasing share of irrigated agricultural production This proportion is much higher in rural and coastal areas where residents have great difficulty accessing fresh water during the dry season due to saline and/or polluted canal water (Danh 2008).

Today, one of the most serious problems in Tra Vinh as other coastal provinces in Mekong Delta is the exploitation of groundwater for different purposes. According to the report prepared by provincial Department of Natural Resources and Environment, there were only 121 abstraction wells which have been reformed the abstraction license until May 2018 with total of abstraction rate about 61,620 m^3/d. So, the variable patterns of groundwater use and the varied services that aquifer systems provide do not form a clear aggregate picture or status of groundwater, nor do they present an opportunity for systematic management response to Tra Vinh province. For that reason, the understanding about pattern and distribution of groundwater use (GWU) plays a key part in ground resources assessment and management at the Mekong Delta in general and Tra Vinh Province in particular.

II. MATERIALS

A. *Study area*

Location

The Tra Vinh Province is situated southwest of Ho Chi Minh City and lies on the coastal plain of the Mekong Delta between the coordinates of 9°31'46" to 10°04'05" latitude and of 105°57'16" to 106°36'04" longitude (Fig.1). The coastal province is part of the lowland area in the Mekong Delta having an elevation range of +2 meters to +0.4 meters. Topography includes coastal plain, alluvial deposits, hundreds of mounds and sand caves, a complex network of rivers and canals.

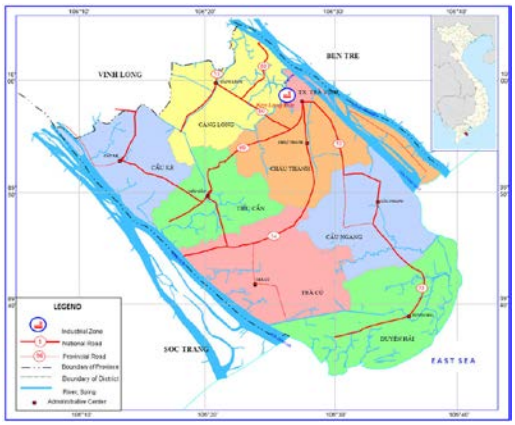


Fig.1. Geographical location of Tra Vinh Province

Climate

Tra Vinh is on tropical monsoon region. The dry season lasts from December to April and the rainy season is between May and November. The weather is hot around the year with the annual average temperature is around 26°C. The annual rainfall data indicates a spatial variation within Tra Vinh Province. Total rainfall is from the medium down to low level (1,588 – 1,227 mm), distributed unevenly and strongly split in accordance with space-time.

Hydrology and hydrogeology

Tra Vinh has a dense network of rivers and canals with two large rivers, Co Chien and Hau Rivers, along with a system of canals that provide water to the fields. The main canals are distributed evently in the province, with the density varies from from 4 to 10 m/ha. The tide is the cause of salinity intrusion into the interior, changing the quality of water in the direction of increased salinity. The hydrogeology of the area is composed eight aquifers that are confined, semi-confined and unconfined aquifers. These aquifer systems are broadly distributed in the area with a thickness of 15 meters to more than 50 meters (Deltares 2011). Aquifer mediums are composed of sand, gravel, pebbles, with a mixture of clay and silt with medium to low water-bearing capacity. Shallow aquifers have low water quality due to the direct interactions in the land surface (Bui, Nguyen et al. 2017).

General socio-ecomonical information

Surrounded by Tien and Hau Rivers and long coast, Tra Vinh's economy is based on agriculture, aquaculture, fish and shrimp breeding. The province is covered by verdant plants in the garden village along the bank of the river. Also, the area is popular for its culture and offers a relaxing tourist visit to its beaches and natural areas. Food production includes crops from agricultural products and mainly fish and shrimps from aquaculture. The Tra Vinh Province used 80% of its land for agriculture and only 0.2% of the total area is urbanized.

B. *Groundwater use reviews*

Groundwater is partially used in aquaculture and is widely used for domestic and industrial purposes. Total amount of groundwater abstraction in Tra Vinh Province is 187,685 m^3/d in 2007 (Sanh N.V, 2010) and the quantity of groundwater was exploited for domestic activities to increase in every year by growing up of number of HH using groundwater and average rate as well (Fig.2).

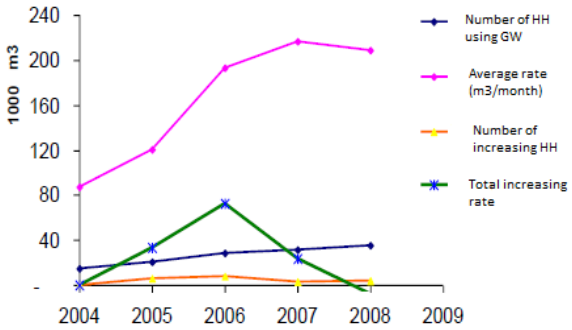


Fig.2. Number of HH using groundwater (Sanh 2010)

In 2010, It is reported that 224,773 m^3/day was abstracted in whole province of which, abstraction amount from wells with capacity ≥ $50m^3/day$ is 53,200 m^3/day and that of wells with capacity <$50m^3/day$ is 200,720 m^3/day (Table 1). Groundwater was mainly abstracted in qp_3 and qp_{2-3} aquifers, a small amount was exploited in qp_1 aquifer, and other aquifers (n_2^2, n_2^1 and n_1^3) were not exploited. Total number of abstraction wells is 88.927 wells, of which number of well with capacity ≥$50m^3/day$ is 114 wells and that of well with capacity <$200m^3/ngày$ is 88.813 wells) (Vuong 2013).

Table 1. HH distribution in Tra Vinh province

No	Aquifer	Groundwater abstraction (m^3/d)		
		Public well ≥$50m^3/d$	Household well <$50m^3/d$	**Total**
1	Holocene (qh)		7,800	7,800
2	Upper Pleistocene (qp_3)	0	73,920	73,920
3	Middle Pleistocene (qp_{2-3})	42,000	119,000	161,000
4	Lower Pleistocene (qp_1)	3,200	0	3,200
whole province		**53,200**	**200,720**	**245,920**

III. METHODOLOGY

In order to estimate pattern and distribution of GWU in Tra Vinh Province, firstly the socio-economic survey was conducted to assess population increase, revenue, land use and water resources issues, especially information relevant to groundwater use for different purposes. Secondly, the survey data was classified and calculated baseline of GWU per each household (HH) and farming area as well as ratio of household using groundwater (RHHUG) to interpolate to other zone. Thirdly, the spatial distribution of groundwater use was simulated by using correlation with land surface temperature

(LST) which was estimated from Landsat 8. In addition, a local groundwater modelling was developed to verify and adjust groundwater abstraction of each district and aquifer to improve piezometric heads based on the observed data.

A. *Socio-economic survey*

Commune survey selection

As the Mekong delta is characteristic of high heterogeneity in both natural conditions including groundwater salinity, 3 different districts were selected for the socio-economic survey to ensure sufficient coverage of local communities with diverse dependency on groundwater to allow understanding local pattern and distribution of groundwater use. The commune selection criteria included assessment of average revenue of local people and status of groundwater and surface water use.

To assess the existing saline groundwater in the study area, the EC (electricity conductivity) test was conducted with totally 751 testing locations and then spatial distribution of the groundwater EC values by using Ordinary kriging. As electrical conductivity (EC) was used to assess the state of existing saline groundwater, the pattern of the indicator "i" is very similar to the EC interpolations previously presented in this study (Villalba 2018) The interpolation of the middle Pleistocene aquifer (qp_{2-3}) is the most reliable of the three aquifers which was conducted EC campaign. It also presents the highest EC values and gradients, in this case, the north-south gradient observed in the other aquifers has a NE-SW component. Brackish and saline groundwater is present only in the northern part of the aquifer study (Fig.3).

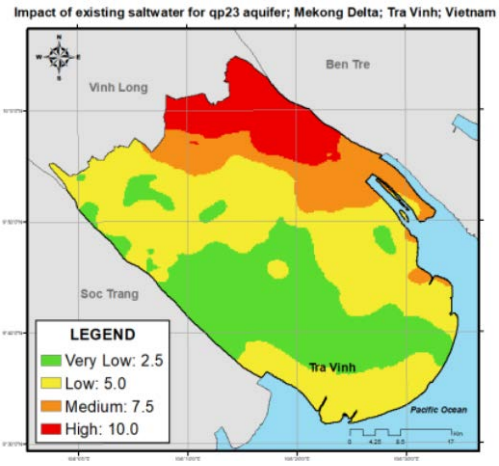


Fig.3. State of existing saline groundwater parameter rating, using the electrical conductivity instead of Cl/HCO3 ratio.

For the surface water, the province can be divided into three regions, namely in the upper zone, the middle zone and the coastal zone. In the upper zone, freshwater is either available at all seasons or depending on the season (see Fig.4). Whereas in the middle zone and coastal zone, they are coping with brackish water and saline intrusion. In addition, Fig.4 also shows that the coastal zone is saline throughout all seasons.

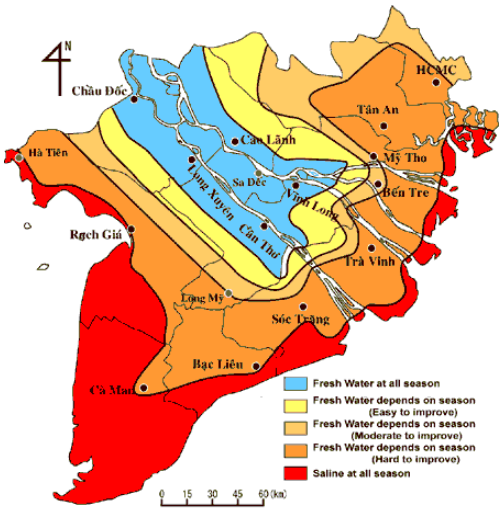


Fig.4. Saline intrusion in the VMD (Scarrott 2009)

Saline intrusion status of both groundwater and surface water were combined to show 5 zones which have different potential water resources as:

- Easy to improve SW + Fresh GW (ESFG)
- Easy to improve SW + Saline GW (ESSG)
- Hard to improve SW + Fresh GW (HSFG)
- Hard to improve SW + Saline GW (HSSG)
- Saline SW all seasons + Fresh GW. (SSFG)

Based on the report of Party congress at the commune level in 2015, three average commune revenue (ACR) levels were determined as high ACR (> 30 mil.dong/year), moderate ACR (20 - 30 mil.dong/year) and low ACR (<20 mil.dong/year). Nine communes were selected by the classification of commune revenue and water resources potential to satisfy the survey can cover five zones and three levels of ACR (see in Table 2).

Table 2. General information of selected communes

District	Commune	Population person	Area ha	Agriculture area (ha)			Income assessment	Potential of WR
				Paddy	Prenial crops	Aquaculture		
Cang Long	My Cam	11,832	2,298	1,006	1,053	0	High	ESSG
	Huyen Hoi	14,244	3,473	2,521	577	4	Moderate	ESFG
	Dai Phuoc	9,520	2,008	409	872	2	Low	HSSG
Tra Cu	Dinh An	5,444	592	168	19	4	High	HSFG
	Thanh Son	9,592	1,415	884	160	4	Moderate	HSFG
	Ham Giang	2,488	1,591	252	239	15	Low	HSFG
Duyen Hai	Long Huu	10,862	3,623	627	316	1,986	High	SSFG
	Truong Long Hoa	5,560	3,751	4	399	3,298	Moderate	SSFG
	Dan Thanh	7,069	4,134	1,230	408	1,248	Low	SSFG

Questionnaire and survey design

The questionnaire was developed on the basis of GWU in each demand and past studies. The questionnaire was used by the interviewer to collect (through face-to-face interview) information from interviewees (i.e., selected respondents from local communities for the survey) for conducting a socio-economic survey. The survey was conducted from 19 to 29 or March 2018 by 6 members of the survey team from Division of Water Resources Planning and Investigation for the South of Vietnam.

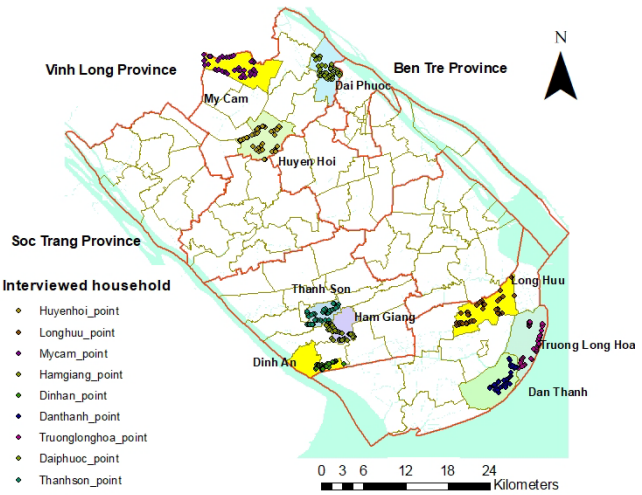


Fig.5. Distribution of interviewed household

Before implemented survey at each commune, the discussion with local authorities to get an overview about water use and land use in the local and ask the head of each village to pick up interviewers to household for surveying. Six villages per each commune were randomly selected to conduct the survey (if the commune has not less than 6 villages). The interviews were mostly conducted with the heads of households. Four 419 questionnaires were interviewed: average about 47 households in each of the nine communes (see questionnaire distribution in Fig.5).

B. Survey data analysis

SPSS tool was applied to statistic the survey data by group classification. Domestic group are formally represented water supply consumption and groundwater pumping by own well. Ratio of HH using groundwater and average pumping rate was calculated to interpolate to whole of district and others using population data. Besides, agriculture group explained irrigation or groundwater abstraction rate which depend on crop and seasonal. Average pumping rate per ha and ratio of HH using GW for agriculture purposes were calculated to interpolate to other parts based on land use data.

C. GWU interpolation

GWU (individual) extrapolation to total by classifications

Ratio of household using groundwater (RHHUG) and average pumping rate of nine survey communes were applied to interpolate other districts which have same of potential of water resources. Besides, ratio of HH using groundwater was estimated by linear regression between ratio of the survey and the previous ratio of Sanh (2010).

GWU expand (individual) to spatial distribution by using LST distribution (Landsat 8)

Landsat 8 OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) images are available and have Thermal Infrared (TIRS) bands (Band 10 and 11, 100 m spatial resolution resampled to 30 meters) that can be used for land surface temperature (LST) with good spatial resolution. In Tra Vinh Province, most of abstraction well located in HH area of near HH area which was used for the agriculture demand of some annual crops. Therefore, LST distribution can be applied to simulated distribution of GWU in where limits data of HH distribution as well as land use.

Correct GWU estimation by using groundwater modelling

In the last section, the ratio of number HH using GW was identified by linear regression between ratio in 2007 (Sanh, 2010) and the ratio in 2016 of the survey. During the groundwater model calibration process, RHHUG of each district was adjusted by annual and seasonal was adjusted to improve piezometric heads based on the observed data.

D. Groundwater modelling process

Groundwater modeling has become a very important process in managing GW resources. Over the past forty years, it was considered to be one of the primary tools, which was used to understand GW flow and seawater movement in coastal aquifer (Todd 1953, Todd and Mays 1980). A transient groundwater flow model (GMS-10.2) was constructed to verify amount of groundwater pumping (pattern and distribution proposed) from 2007 to 2016 using boundary conditions from the regional groundwater model, which covered whole of Mekong Delta area (Vuong 2013). The domain of the model has an area of 2,215 km^2. The hydrogeological conceptual model consists of eight aquifers separated by seven aquitards. The aquifers and aquitards are heterogeneous (Deltares 2011). The model grid consists of 135 rows and 151 columns with a uniform grid size of 500 x 500 m. The layers of 2, 4, 6, 8, 10 and 12 represented for aquitards or impervious layers. Layers of 1, 3, 5, 7, 9, 11 and 13 represented for aquifers qh, qp_3, $qp_{2\text{-}3}$, qp_1, $n_{2\text{-}2}$, $n_{2\text{-}1}$, and $n_{1\text{-}3}$ respectively. General head and specify head boundary were assigned and each aquifer had different boundary conditions base on observed data and the regional model (Vuong 2013). Geostatistic tools (GMS) was applied to simulate hydraulic conductivity distribution of 8 layers. The potential recharge zones in a spatial scale was produced based on the analysis, field and laboratory results, and available data used in Tra Vinh province (Silva 2018). The potential amount of recharge can vary from 8% to 12% of total annual precipitation. The water levels were simulated by using MIKE11 (Tri 2016) to input by river and canal nodes in the groundwater flow modelling. In addition, the river conductance from previous model (Boehmer 2000) was applied to simulate the river leakage of the first aquifer. From upper estimation, initial groundwater abstraction of each district and aquifer was by year and seasonal from 2007 to 2016.

IV. RESULTS

A. GWU estimation (individual)

Domestic group

Most of HH still has used own groundwater well for domestic, it occupied around 80 percentage of total number of household in coastal zone. In northern district, RHHUG is lowest; around 23 % as Huyen Hoi commune, some of communes even did not use groundwater due to high salinity concentration of groundwater in this part. VPR per HH varied from 1.05 m^3/HH/d to 2.05 m^3/HH/d and its trend increased from Northern part to Coastal part (Table 3).

Table 3. Calculation of GWU for domestic in 9 survey communes.

Commune	Number of HH survey	Bottle water		In-house tap water		Own well	
		RHHUG (%)	APR m^3/HH/d	RHHUG (%)	APR m^3/HH/d	RHHUG (%)	APR m^3/HH/d
My Cam	47	0	0	0	0	0	0
Dai Phuoc	46	0	0	0	0	0	0
Huyen Hoi	47	23	0.007	49	0.191	87	1.05
Thanh Son	47	38	0.005	45	0.189	74	2.20
Ham Giang	45	45	0.003	47	0.374	84	1.87
Dinh An	47	17	0.005	74	0.503	43	1.80
Long Huu	47	72	0.006	45	0.297	91	3.42
Truong Long Hoa	48	79	0.004	43	0.256	85	3.74
Dan Thanh	45	89	0.007	38	0.617	84	4.38
Average	**46.6**	**40**	**0.004**	**38**	**0.270**	**61**	**2.05**

Agriculture group

In dry season, groundwater was exploited much more to balance salinity of aquaculture farm in coastal and near coastal zone. Abstraction time always was gained continuously 15 to 20 days during salt intrusion period with average rate over 4.36 m^3/d/ha (total 41.8 m^3/ha of whole farming season). On the other hands, groundwater is main irrigation source of some annual crops such as water melon, pepper, onion, etc., in duration from January to April of the dry season. The calculation showed that the APR for irrigation of some annual crops was about 30 m^3/d/ha (as in Table 4).

Table 4. Calculation of GWU for domestic in 9 survey communes

Commune	Aquaculture		Irrigation	
	RHHUG (%)	APR (m^3/ha/d)	RHHUG (%)	APR (m^3/ha/d)
My Cam	0	0	0	0
Dai Phuoc	0	0	0	0
Huyen Hoi	0	0	0	0
Thanh Son	0	0	93	24.84
Ham Giang	1.50	3.69	95	33.38
Dinh An	1.60	4.58	91	32.06
Long Huu	1.80	3.60	97	30.83
Truong Long Hoa	1.90	4.22	98	26.98
Dan Thanh	2.60	5.73	97	32.19
Average	**1.88**	**4.36**	**95**	**30.05**

B. *Groundwater interpolation*

The study investigated the correlation between the estimated GWU by statistic data including number of HH and land use at the commune level of Tra Cu district and estimated GWU by LST from Landsat 8 Image (acquisition date 2-22-2014). The correlation reveals that GWU estimation using LST distribution shows a statistically significant positive correlation to the GWU estimation using statistical data (adj-R2 = 0.646) (Fig.6).

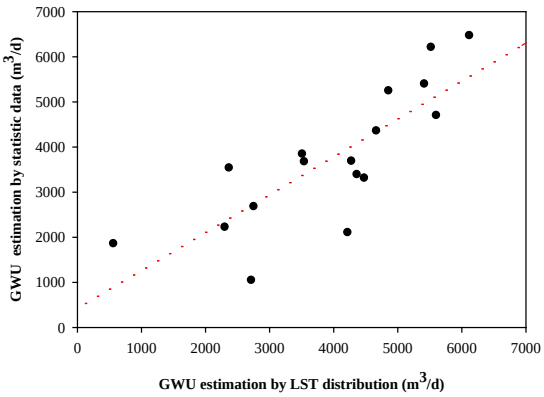
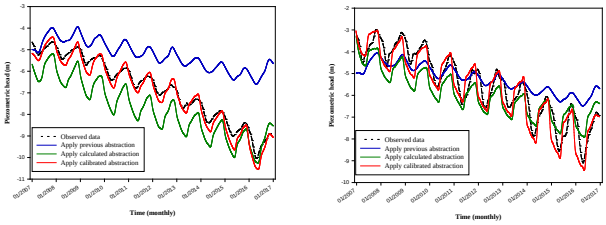


Fig.6. Scatter plot of GWU estimation in 17 communes of Tra Cu district using statistical data and LST distribution

Results of calibration model show that computed values of the previous GWU are much higher than observed data. The calculated GWU improved piezometric heads to be closer relations with observation data in last 2 years (Fig.7). Groundwater abstraction (GWA) was adjusted by changing the ratio of HH using GWU of each district and ratio using GWU by seasonal as well.



a) Q404030 (qp_3 aquifer) b) Q217030 (qp_{2-3} aquifer)

Fig.7. Piezometric heads comparison by applying different abstraction pattern and distribution

Table 5 shows the corrected ratio of HH using groundwater via groundwater model calibration process. Due to salt intrusion in dry season, groundwater tends to be exploited more and in coastal zone to satisfy domestic and agriculture demand. It is reason why ratio of HH using groundwater in the coastal zone increased around double during past 10 years (Table 5).

Table 5. Ratio of HH using groundwater by districts from 2007 to 2016

Year	Number of HH	Ratio of HH using groundwater (%)							
		Cang Long	TP	Cau ke	Tieu Can	Chau Thanh	Cau Ngang	Tra Cu	Duyen Hai
2007	220,869	34%	6%	64%	43%	48%	33%	26%	40%
2008	221,665	42%	9%	73%	56%	58%	49%	33%	43%
2009	222,193	43%	8%	63%	55%	57%	43%	35%	39%
2010	222,789	43%	8%	58%	55%	57%	45%	37%	45%
2011	224,293	43%	7%	63%	55%	57%	45%	39%	56%
2012	225,590	45%	11%	62%	59%	60%	48%	37%	61%
2013	226,786	47%	8%	65%	62%	62%	53%	40%	60%
2014	228,004	49%	9%	68%	66%	65%	56%	48%	76%
2015	229,045	51%	10%	71%	70%	67%	59%	61%	69%
2016	231,238	53%	10%	73%	74%	70%	61%	83%	71%

C. *Groundwater use pattern and distribution*

GWU concentrated mainly in coastal zone with over 67 percentages (234,476 m^3/d) of total GWU in Tra Vinh Province. From 2007 to 2016, GWU of Tra Cu and Duyen Hai increased rapidly from 48,200 m^3/d and 51,127 m^3/d to 94,648 m^3/d and 90,903 m^3/d respectively (as Table 6).

Table 6. Annual GWU at HH level by districts from 2007 to 2016

Year	Number of HH	Annual groundwater use (m^3/d)								
		Tp. Tra vinh	Cang Long	Cau Ke	Tieu Can	Chau Thanh	Cau Ngang	Tra Cu	Duyen Hai	Total
2007	220,869	5,877	10,102	24,417	26,579	30,476	33,585	46,415	65,915	**243,365**
2008	221,665	6,419	10,599	26,745	27,351	34,175	34,994	51,073	69,714	**261,071**
2009	222,193	7,164	11,044	25,482	28,516	38,910	39,473	55,769	74,988	**281,346**
2010	222,789	7,752	11,686	25,368	29,384	40,652	41,409	59,804	77,164	**293,220**
2011	224,293	8,692	12,373	27,198	30,404	45,109	43,946	64,245	78,337	**310,305**
2012	225,590	8,704	13,019	27,765	31,250	46,532	46,770	70,862	82,060	**326,962**
2013	226,786	9,967	13,697	29,153	32,238	48,825	49,155	75,850	86,358	**345,243**
2014	228,004	10,665	14,359	30,523	33,084	52,009	52,009	81,039	90,313	**364,001**
2015	229,045	11,411	15,045	31,952	33,817	54,510	54,705	22,060	90,871	**314,371**
2016	231,238	12,146	15,745	34,428	34,735	55,776	57,936	89,819	96,221	**396,806**

D. Groundwater budget

From the groundwater model results, the model estimated total inflows including land recharge, river recharge, leakage and boundary were always smaller than total outflow. Although aquifer qh absorbed total of river recharge and land recharge in the whole study area, however sum of discharge by pumping and filtration to below aquifer (qp_3 aquifer) was approximated to be about 128,320 m^3/d. It means that the changing storage of qh aquifer is low and it was also explained by the stable fluctuation of piezometric heads in duration from 2007 to 2016 in two main aquifers (qp_3 and qp_{2-3}) (Fig.8)

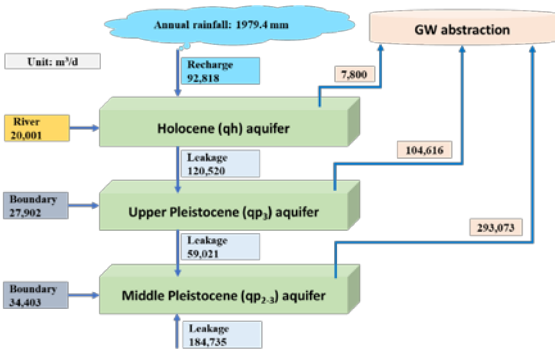


Fig.8. Groundwater budget of three top aquifers in 2016

In qp_{2-3} aquifer (main abstracted aquifer), 82 percentage of inflow was leakage flow with lower and upper aquifer. However, the over GWA reduced the storage of aquifer due to decline GWL significantly in the period of 10 years.

CONCLUSIONS

In northern part, where most groundwater is brackish and saline, the ratio of HH using groundwater is only 44 percent at present. However, in middle part and coastal part, their ratios were 83 percent and 73 percent, respectively. Average rate of GWU in coastal part also was much higher than the rate in northern part, particular is 3.78 m^3/HH/d and 1.05 m^3/HH/d.

Ratio of HH using groundwater in each part was different. It varied from 61 percent to 83 percent in coastal part and middle part and around 50 percent in northern part, respectively. In 2016, annual GWA was estimated to be 347,793 m^3/d in which sum of Duyen Hai, Tra Cu and Cau Ngang district occupied about 67 percent. LST presented a good correlation with GWU distribution with R^2 = 0.646. In future, it can be applied to estimate GWU in other area and in regional scale.

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