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Managing shallow aquifers in the dry zone of Sri Lanka

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Abstract This study looks at the groundwater issues in the dry zone of Sri Lanka and shows how the use of remote sensing with high-resolution images can help in groundwater management. A new approach is developed for automatic extraction of the location of agro-wells using high-spatial-resolution satellite imageries. As an example, three pilot sites in three different aquifer systems in the country are considered, and their high-resolution images are analyzed over two temporal time periods. The analysis suggests that the well density in all three regions has increased over the last few years, indicating higher levels of groundwater extraction. Using the well inventory developed by this new approach, the water budgeting was prepared for the mainland of Jaffna Peninsula. The analysis shows a wide variation in well density in the Jaffna Peninsula, ranging from (as little as) less than 15 wells per square kilometer to (as high as) more than 200 wells per square kilometer. Calculations made for the maximum allowable water extraction in each administrative division of Jaffna show that less than 3 h of daily extraction per well is possible in some districts. This points to an increasing pressure on groundwater resources in the region and thus highlights the importance of understanding groundwater budgets for sustainable development of the aquifers.

Keywords Agro-wells · Groundwater · Shallow aquifer · Remote sensing · Water budgeting

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Introduction

Sri Lanka, an island country with an area of 65,610 km^2 and a current population of 20.3 million (as of 2009, from the World Development Indicators of the World Bank), has annual available freshwater resources estimated in the range of about 1850 m^3/capita (calculated based on (Ariyabandu and Aheeyar 2004)) to about 2592 m^3/capita (Villholth and Rajasooriyar 2010). At the national scale, water availability per capita values are much higher than the water scarcity indicator of 1000 m^3/capita (http://www.un.org/waterforlifedecade/scarcity.shtml, accessed in June, 2013). However, like any other natural resource, the availability of freshwater in Sri Lanka varies spatially and temporally.

The geographic conditions and meteorological parameters create a situation of water-rich and water-scarce regions within Sri Lanka. Based on the regional rainfall, the country is divided into three zones—wet, intermediate, and dry zones. Monsoonal rains are the main source of freshwater. The northern, central, and eastern parts of the country receive, on average, less than 1500 mm of annual rainfall and are referred to as the "dry" zone. The western and southwestern parts of the country receive more than 2500 mm of annual

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rainfall and are referred to as the "wet" zone. The region between the wet and dry zones forms the Intermediate zone.

Besides receiving lesser volumes, rainfall in the dry zone is concentrated over the short period of 3 months from December to February. The dry zone also has a higher evaporation rate, i.e., evaporation from a free surface, which is as high as 6 mm per day during the dry season compared to 2.5–3.5 mm/day in the wet zone (Panabokke 1996). In these regions, people predominantly depend on groundwater to meet their water needs. The shallow wells serve as the only source of water for irrigation and domestic purposes. The relatively thin (not more than 25 m) weathered zone of the dry zone also has limited capacity to store groundwater. This is mainly because of the geological structure in these regions.

Traditionally, in Sri Lanka, shallow aquifers in the dry zone are harvested by manually dug shallow wells. Such wells, which are predominantly used to meet agricultural water demand, are called agro-wells. These wells are typically circular with 4.5 m in diameter and 5–8 m deep. With a small pump, farmers can typically irrigate 0.2 to 0.8 ha. Since the 1980s, encouraged by the government and nongovernmental organizations (NGOs), there has been a proliferation of shallow wells in dry zone of Sri Lanka. These were meant for irrigation of crops in the *Yala* (dry) season and to supplement water requirements in the *Maha* (wet) season at times of water shortages. The agro-wells are helping to change the agricultural practices in some parts of the North Central Province. Farmers are shifting from traditional paddy farming to the cultivation of high-value crops, such as onions, chilies, banana, etc., along with higher cropping intensity—up to two to three cropping cycles per year. Due to the increase in the number of agro-wells, farm-based incomes and employment have increased (Shah et al. 2013). Some of these high-value crops are helping to improve the nutrition status of the families. It is not just agriculture that benefited from the agro-wells; farmers also use the water for domestic purposes (bathing, washing, cooking, and sanitation), brick making, and watering livestock.

The boom in agro-wells has led to groundwater issues. In these dry zones, due to the high water table, access to groundwater seems very easy and gives a false sense of the unlimited supply of freshwater. Yet, because of its invisibility, groundwater is not managed well. After the end of the civil war (which was mostly concentrated in the dry zone of the country) in 2009, as the focus shifted to development in these regions, it became critical to have a good understanding of groundwater resources, their availability, and use. The groundwater issues in Sri Lanka can be grouped under management (well drying and water quality) and governance (policy, institutional and legal).

Many wells in the dry zone are going dry (Jayakody 2006). This is either due to the wrong "siting" of the wells or due to overextraction of groundwater resources. During the "agro-well rush" in the 1980s and 1990s of the last century, no proper geological studies were carried out before siting a well. In some micro-catchments, the drying up of wells may also be due to overexploitation of groundwater resources; i.e., extraction has exceeded the carrying capacity, leading to a net depletion of the water table in these areas. Such wells were subsequently abandoned. The pollution of groundwater is becoming one of the major problems in Sri Lanka. There are two reasons for the poor water quality in Sri Lanka: (a) urban and agricultural pollution of aquifers, i.e., anthropological, and (b) the natural geochemistry of the area, i.e., natural. There is a suspicion that leaching of some elements from overuse of agrochemicals in the dry zone has polluted the groundwater (Wijesinghe and Thiruchelvam 2003). It is also suspected that groundwater polluted with agrochemicals is a cause for health issues, such as chronic kidney disease of unknown etiology (popularly known as CKDu). Tens of thousands of people are now suffering from CKDu in several provinces, in particular, the North Central Province. The Jaffna and Kalpitiya peninsulas are two areas under intensive agriculture in the dry zone, both producing important secondary food crops. In the islands off the peninsulas, 50 % of the wells contained nitrate levels above 10 mg/l. Other studies have found high levels of nitrate-N in groundwater (Mikunthan and de Silva 2009; Jeyaruba and Thushyanthy 2009), which have been directly related to agricultural activities ((Jayasingha et al. 2011; Liyanage et al. 2000); Kuruppuarachchi and Fernando 1999; (Nagarajah et al. 1988)). Overextraction of groundwater resources has also contributed to saltwater intrusion and higher nitrate loads in the groundwater (Jayasekera et al. 2011; Jayasekera 2007). The existence of too many wells also leads to salinization of the aquifer (Nandakumar 1983). Approximately 5 % of the Jaffna aquifer has been salinized (Pathmanathan 2004). A hydrochemical analysis of groundwater in the Jaffna Peninsula found that, if electrical conductivity was used as a measure of salinity, about 44 % of the wells had medium salinity, 47 % had high salinity, and 9 % had very high salinity (Nishanthiny et al. 2010).

On the governance front, Water Resources Board (WRB) and the National Water Supply and Drainage Board (NWSDB) are responsible for scientific investigation and operational development of the groundwater, respectively. These two organizations are also responsible for maintaining scientific data on groundwater resources. The government administration operates at the four levels of central, provincial, district, and divisional. In the devolved structure of the government, the central and provincial levels are responsible for planning, budgeting, monitoring, and review. WRB and NWSDB are established at national level. The district, including municipal and urban councils, takes care of backstopping, coordination, and major implementation activities, while the divisional level is responsible for on-the-ground implementation of program components and delivery of services. No comprehensive, consistent, and coordinated data exists for groundwater in the country (Samad 2005). There are over 50 legislative enactments and 42 institutions dealing with water-related matters in Sri Lanka. This has caused more complications than benefits and has impeded water management in Sri Lanka. For good management, proper coordination, clear responsibilities, effective watershed management, and active public participation are essential. At the same time, there is no management of groundwater.

As seen above, there is a need for improved management and governance for aquifer systems in dry zone of Sri Lanka. This will not only help in sustainable harnessing of the groundwater but also help in improving the quality of groundwater. For proper groundwater management, a good inventory of wells is a necessity. The number of wells can be used as a proxy for groundwater use, but the data on wells that exist in the country, especially the "agro-wells," is limited. At best, the data are available in regional agrarian development offices, based on field visits made by the extension officers. Some studies have tried to estimate the number of wells, for example, in the dry central zone ((Kikuchi et al. 2003); Panabokke 1998), but it is based on rough estimates. With easy accessibility to higher computational power, it is now possible to use high-resolution satellite images to monitor propagation of wells within an aquifer system. A methodology is developed and presented that uses high-resolution remote sensing images to build an agro-well (shallow well) inventory. This is critical for creating an accurate inventory of wells—a precondition to science-based management. The methodology is tested in three separate aquifer systems in the country. These aquifer systems, although different in geological terms, are mostly characterized by shallow wells. Knowing the basic water budget in an aquifer is a prerequisite for developing a science-based groundwater policy; this methodology is then applied to Jaffna region of dry-zone Sri Lanka to conduct a quick groundwater budgeting. Two factors that are critical for groundwater budgeting are the rate of extraction and quantity of extraction. The rate of extraction determines how fast the aquifer is depleted. The quantity of extraction determines the sustainability of groundwater in the region. Both of these factors are influenced by the well density in a region.

In the following sections, first, the three aquifer sites and the Jaffna region are described. Second, the methodology to use high-resolution imagery to build agro-well inventory, along with methodology to calculate groundwater recharge, is discussed. Finally, in the "Results and discussion" section, the results from the well-inventory of the three pilot sites and use of such inventory in groundwater balance in the Jaffna Peninsula and its inferences are discussed.

Study areas

The dry zone of Sri Lanka is made up of different aquifer systems; i.e., the aquifer systems have varied geomorphological and hydrogeological characteristics (Panabokke and Perera 2005). The three pilot sites (each from a different aquifer system) and Jaffna District considered in this study are shown in Fig. 1, and a brief description is provided below:

1. Valikamam South (Uduvil) Divisional Secretariat (DS) division in the Jaffna District: shallow karstic aquifer; area considered—36.2 km^2; population—57,266; and major crops—small onion, tobacco, black gram, betel, chilies, finger millet (*kurakkan* in local language), cowpea, and sesame. This area falls under the Miocene sedimentary limestone domain that is commonly located in the northwest and north coastal regions of the island. In Jaffna District, the only source of the groundwater is through rainfall from northeast monsoons, which are prevalent

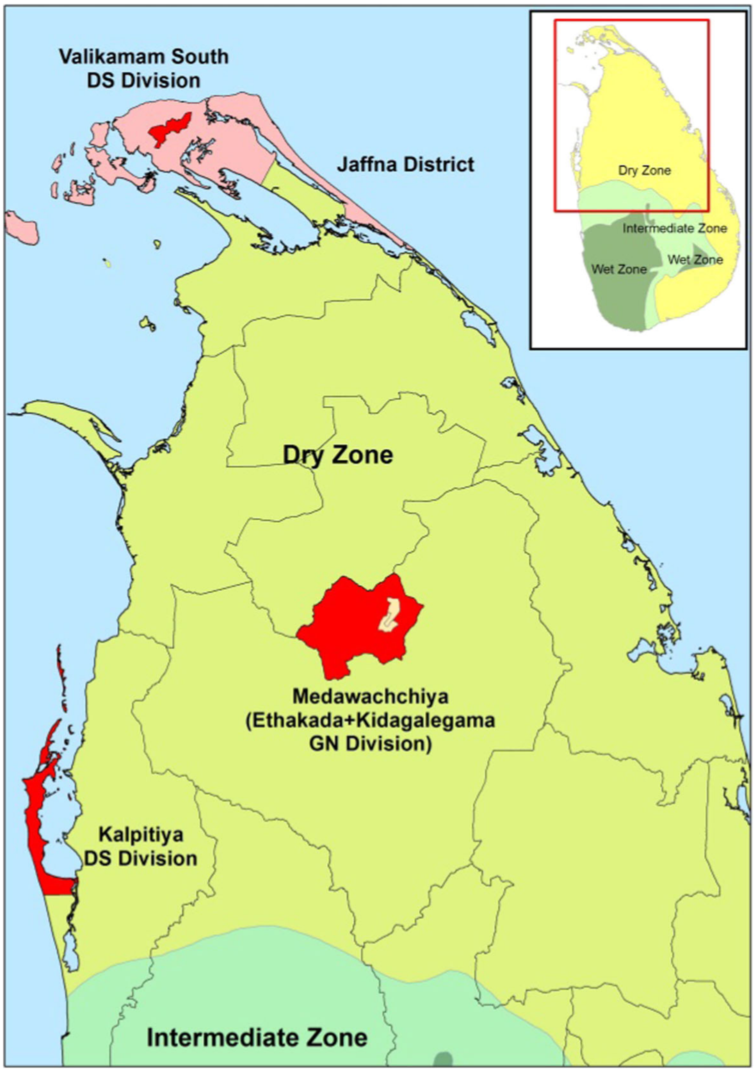

Fig. 1 Study areas

from November to December. The shallow aquifers are formed in the channels and cavities of highly karstified Miocene limestone formation. Due to the karst nature of the underlying rock, about 50 % of the groundwater is lost to the sea. About 80 % of the extracted groundwater is used for irrigation, and the remaining is used for domestic purposes (Panabokke and Perera 2005).

2. Ethakada and Kidagalegama Grama Niladhari (GN) divisions in the Medawachchiya DS division of Anuradhapura District: shallow regolith aquifer of north-central region; area considered—528.9 km^2; population—40,621; and major crops—brinjal, chilies, ladies fingers, tomato, and big onion. This area falls under the crystalline basement complex and is the main hydrogeological domain in the hard rock regions of Sri Lanka. The potential for groundwater development under this type is limited ((Hettiarachchi 2008); Panabokke and Perera 2005). In this region, groundwater exists either as shallow, disconnected small bodies of water in the weathered rock zone (called the regolith) or within the deep fracture zone of the rocks. The regolith aquifer is confined to the narrow belt along the inland valley (Panabokke and Perera 2005). Along with recharge from rainfall, the aquifers also get recharged during the dry season from the tank system in the region.

3. Kalpitiya DS division in Puttalam District: shallow coastal sand aquifer of Kalpitiya Peninsula; area considered—167.4 km^2; population—80,258; and major crops—cabbage, onion, chilies, pumpkin, watermelon, guava, papaya, cauliflower, brinjal, and cucumber. These types of aquifers are common in the eastern coastal belt. The thickness of the water lens varies from 10 to 20 m. In Kalpitiya Peninsula, the aquifer forms a very narrow and thin lens of freshwater over denser saline water. Although small in size, it supports intensive agricultural practices and other domestic needs. The only source of recharge for this aquifer is through rainfall, which limits the recharge months to 3–4 months during the *Maha* season.

The geological domains in relation to groundwater are discussed in great detail by Panabokke (Panabokke 2008) and Panabokke and Perera (2005).

Methodology

Agro-well identification

In this study, a new approach was developed for automatic extraction of the location of agro-wells using high-spatial-resolution satellite imageries. ERDAS Imagine, ERDAS Objective, and ArcGIS were used for pre- and post-image processing work. All image tiles were mosaicked. To make interpretation easy and efficient, "*HPF Resolution Merge*" was applied to pan-sharpen the images. Since our objective was to identify the agro-wells, it made sense to focus only on the area of land under agriculture. Thus, first, the agricultural area was extracted. Second, the object-based classification was applied only to the agricultural area to identify agro-wells. Therefore, object parameters were identified to automate the process.

The objective module available in the ERDAS imagine was used to extract the agriculture area and the agro-wells. The process of agricultural area extraction is shown in Fig. 2. To extract agriculture area, different agricultural fields (i.e., with various stages of crops and fallow) were identified visually. For each of these different agricultural fields, training samples were created to calculate the "single-feature probability" (SFP). SFP is a pixel parameter that computes the probability metric (a number between 0 and 1) for each pixel of the input image based on its pixel value and the training samples. Then, the "segmentation" operator was applied to the SFP layer to group similar values into a single segment. For this process, "minimum value difference" and "variation factors" were fixed. This resulted in a segmented image with the zonal mean pixel probability values as attributes. Various filters such as "focal majority" filter and "Size" filter were applied to remove unwanted segments and to get the right shape of the object. Subsequently, the segments were converted to vector using "polygon trace" operator, and finally, probability threshold was applied to separate the agriculture polygons from other land use vector polygons.

Once the agriculture land area was extracted, a similar approach was applied for extracting locations of agro-wells. Using the training samples for the well, the probability layer was created and probability threshold was applied to select the features with the highest probability of being an agro-well. The *RECLUMP* and *DILATE* options were applied to smoothen the selected objects and get the shape of the objects correct. The objects were then converted to vector for geometrical filtering or cleaning. The parameter values of 2–10 m for size and a value greater than 0.6 for circularity were used for cleaning. Finally, template matching was carried out to get the shape of the agro-wells. The process of agro-well extraction is explained graphically in Fig. 3.

Groundwater recharge

The groundwater-level fluctuation method was employed to study and map spatial and temporal patterns of groundwater recharge. This is an indirect method of deducing the recharge from the fluctuation of the water table and was based on the site-specific conditions in the Chunnakam areas of the Jaffna Peninsula (Fig. 4). The region has a distinct rainy season while the remainder of the year is relatively dry; thus, the rise in the water table during the rainy season can be used to estimate the recharge. Due to the flat nature of the topography, it was assumed that all the surface and subsurface inflows are equal to outflows during a relatively short rainy season. Further, due to the absence of irrigation canals, surface storage tanks and perennial rivers in the Chunnakam areas, and recharge components associated with secondary sources such as canals and rivers, can be safely ignored. It is recognized that other factors, such as pumping or irrigation during the rainy season, do not

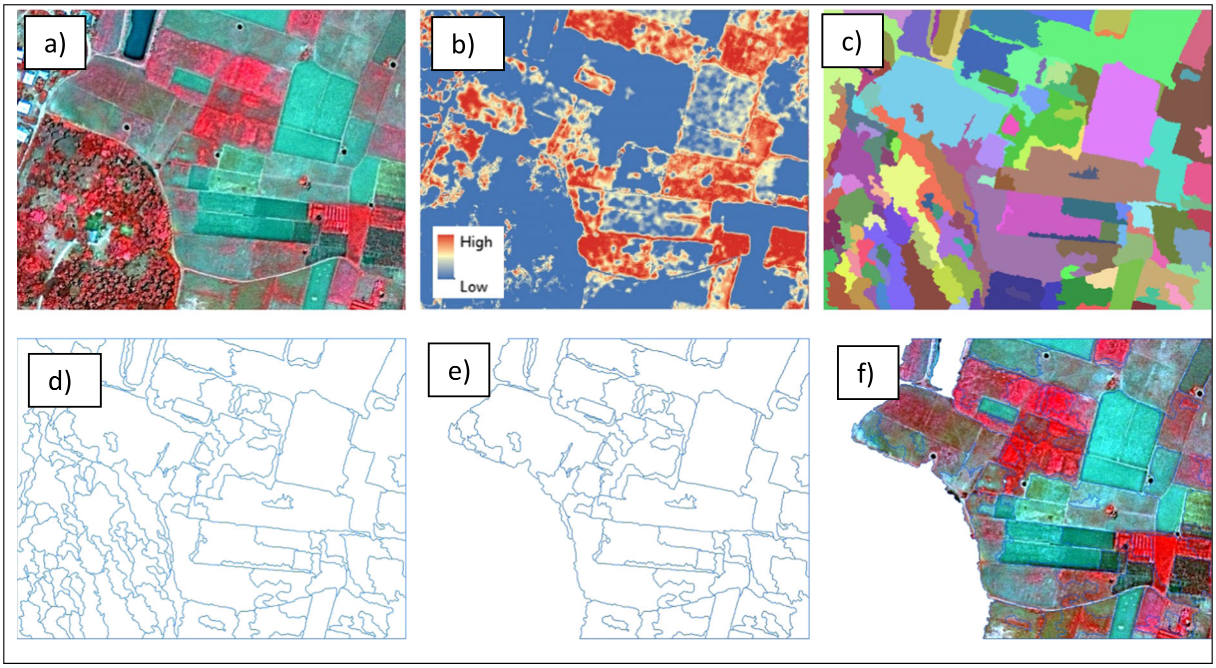

Fig. 2 Extraction/separation of agricultural land areas: **a** original XS image, **b** probability for a one class, **c** segmented and filtered image, **d** segment converted vector, **e** extracted vector after applying the probability threshold, and **f** extracted agriculture lands

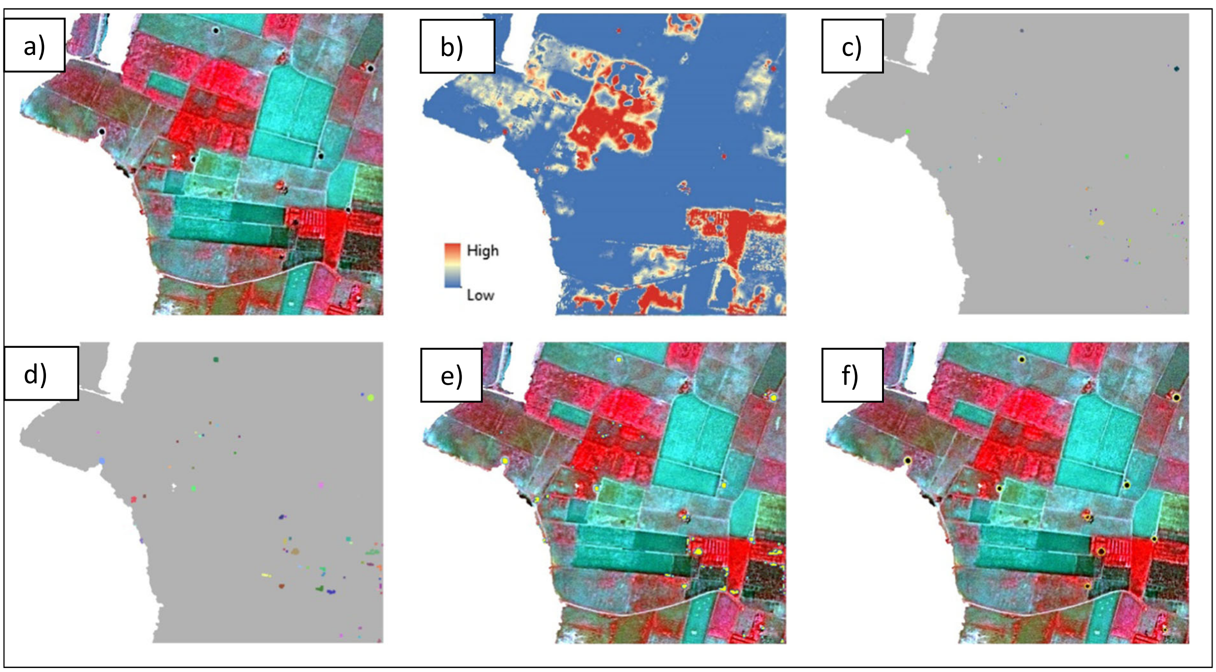

Fig. 3 Process followed to extract agro-wells using high-resolution imagery: **a** Agriculture masked image from pan-sharpened image, **b** probability layer for wells, **c** pixels selected using probability threshold, **d** filtered pixels of wells, **e** converted vector objects, and **f** agro-wells on the agricultural land after performing geometric cleaning and template matching

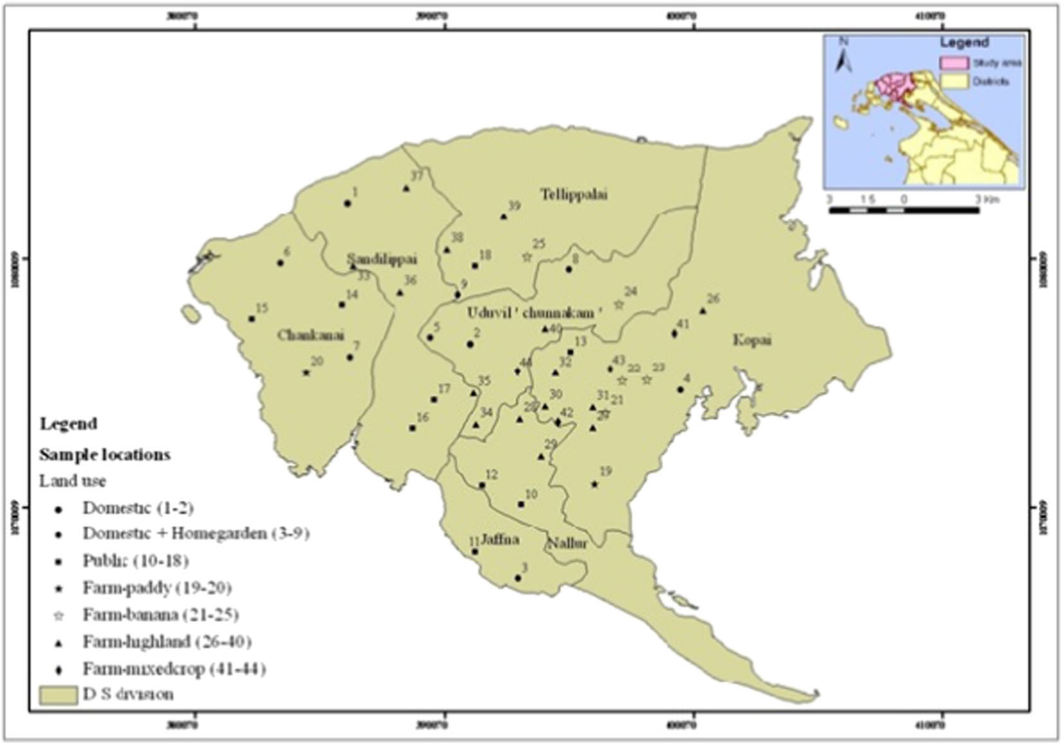

Fig. 4 Well location of test wells in the Valikamam area of Jaffna Peninsula

have an influence. Furthermore, the soil is assumed to be at its maximum water-holding capacity during the rainy season, and any excessive irrigation or rainfall over evapotranspiration will reach the groundwater. If the rise in the water table is Δw, the rainfall recharge, Ri, is estimated using Eq. (1) below:

$$\mathrm{Ri} = \mathrm{Sy}\Delta w + \mathrm{TP} - \mathrm{RT} \tag{1}$$

where Ri=rainfall recharge (m), Sy=specific yield, Δw=rise in the water table (m), TP=abstraction (m), and RT=irrigation return flow (m)

Fluctuation in groundwater level (Δw) was monitored periodically by taking into consideration the water levels of 44 spatially distributed wells (Fig. 4). The Thiessen polygon technique was used to estimate the area unit represented by each measuring point and to compute the average storage gain or loss in the aquifer.

During the period when the water table is shallow and the soil remains highly moist, it could be assumed that any draft from groundwater in excess of evapotranspiration (ET) would return to the groundwater during field irrigation without contributing to soil moisture storage. Thus, Eq. (1) can be reduced to Eq. (2) as shown below.

$$C'\mathrm{Rf} = \mathrm{Ri} = \mathrm{Sy}\Delta w + \mathrm{ET} \tag{2}$$

or

$$C\mathrm{Rf} = (\mathrm{Ri{-}ET}) = \mathrm{Sy}\Delta w \tag{3}$$

where Rf=total rainfall during the period of study (m) and C' and C=fraction of the rainfall that contributes to groundwater recharge.

(SyΔw+ET) in Eq. (2) is considered as gross recharge and SyΔw in Eq. (3) is considered as net recharge. The coefficient C compounds the effect of all the unknown components in the water balance equation, including ET.

The basic limitation of Eq. (2) is that it neglects the subsurface inflow and outflow and assumes that every inflow and outflow is uniformly distributed over the area. Therefore, as suggested by Kumar (Kumar 2003), the use of Eq. (2) should be limited to distinct rainy periods. Moreover, it depends on the value of the specific yield, which is difficult to determine because fluctuation of the water table occurs in the partially saturated zone whereas the specific yield value determined by the pumping test is applicable to the aquifer system.

Results and discussion

Selecting suitable satellite images was a challenge in this study. To identify the changes in agro-well density over time, the images had to be selected for the three study areas for two time periods. For this study, 0.5-m resolution imageries were preferred. Another constraint in selecting imagery for this study was getting cloud-free images. Clouds are especially a problem in Sri Lanka because of its tropical location. Thus, it was not possible to obtain cloud-free 0.5-m resolution images for the same time period for all the three regions. As shown in Table 1, different available high-resolution images such as IKONOS, QuickBird, GeoEye, and WorldView were selected for the two periods.

All the images selected for this study were geometrically corrected and geo-referenced to UTM Zone 44 with spheroid and datum in WGS 84. There was no haze or cloud presented in the images. The quality of the images was good enough to perform the classification.

To assess the accuracy of the method employed to identify the agro-wells, a ground survey was conducted in Jaffna District. During the survey, 646 randomly selected points (agro-wells) were observed in the field and the accuracy matrix (Table 2) was developed.

Out of 646 surveyed agro-wells, 64 were not identified using the applied methodology. Out of 64 missed agro-wells, 60 were covered by trees and made it difficult, if not impossible, to be visible through satellites. However, only one agro-well was wrongly identified as an agro-well.

The overall accuracy achieved was 90 % with a producer's accuracy of 90.08 % and user's accuracy of 99.83 %. The error of omission is calculated as 9.92 % whereas the error of commission was 0.17 %.

Table 3 shows the total land area, calculated agricultural land area, and the number of agro-wells for each study area for the two temporal periods.

According to the image of 2003, the total agricultural land area of the Valikamam South DS division is 12.07 km^2 and the number of wells is 796. However, in 2009, the total agricultural land area and the number of wells increased to 12.79 km^2 and 1090, respectively. This result shows that the number of wells in the Valikamam South DS division has significantly increased during this 6-year period.

In the Ethakada and Kidagalegama GN divisions of the Medawachchiya DS division, the analysis from 2004 to 2010 shows that the total agricultural land area has decreased from 9.8 to 8.36 km^2, and the number of agro-wells has increased from 188 to 256. The decrease in the total agricultural land area is due to abandonment of agricultural land. There is no conclusive evidence as to why these agricultural lands were abandoned. It could be either due to the practice of *Chena* cultivation in that area. *Chena* means slash-and-burn cultivation. Farmers in the Medawachchiya area burn the natural forest and use the land area for cultivation for some time. After a while, they abandon that area and leave the land fallow, allowing the soil to regain its fertility. It is possible that the lands were abandoned due to the failure of agro-wells, but it is difficult to provide any evidence to reach such a conclusion. It has been calculated that 2.47 km^2 of agricultural land has been abandoned from 2004 to 2010. Comparing the 2004 and 2010 images, it was also analyzed that 1.03 km^2 of new agricultural land

Table 1 Most suitable high-resolution imageries that were selected for the study

Study area	Sensor	Date	Resolution pan (m)	Resolution maximum (m)
Valikamam South	QB02	12 May 2009	0.6	2.4
	IKONOS2	1 Jan 2003	1.0	2.0
Kalpitiya	WV2	29 Jan 2010	0.5	2.0
	IKONOS2	24 May 2001	1.0	4.0
Medawachchiya	QB02	29 Feb 2004	0.6	2.4
	GeoEye-1	1 Jun 2010	0.5	2.0

Table 2 Accuracy matrix: comparing satellite-based data with ground truthing

		Ground	
Image		Agro-well	No agro-well
	Agro-well	581	1
	No agro-well	64	–

was added during the same time period. Other factors, such as security risks or migration due to economic reasons, may have also led to abandonment of agricultural land.

In the Kalpitiya DS division, although the number of agro-wells increased between 2001 and 2010, the total agricultural land area also increased for the same time period, and thus, agro-well density had not changed significantly.

The change in the well density was calculated for the total land area and total agricultural land area of the three pilot regions. From these results, it is seen that the well density in all the three regions is on the rise. In 6 years (from 2003 to 2009), the total agricultural land area in Valikamam increased from 0.33 % of the total land area to 0.35 %. In the same time period, well density increased from 66 to 85 wells/km^2 of total agricultural land area. If the total land area is considered, well density increased from 22 to 30 wells/km^2. This rate of increase in well density is about 37 % for the entire region. In Medawachchiya, for the 6-year period (from 2004 to 2010), the total agricultural land area actually decreased from 0.33 to 0.28 % of the total land area, but the number of wells increased. Although the well density in this region is much lower than in Valikamam (increased from 19 to 30 wells/km^2 of total agricultural land area), the rate of increase in well density per hectare of agricultural area was much higher. In the Medawachchiya region, well density increased by almost 60 %, if only the total agricultural land area is considered. However, if the total land area is considered, the well density in both Valikamam and Medawachchiya regions increased at almost the same rate, i.e., 36 %. In the Kalpitiya Peninsula, the total agricultural land area increased from 38 % of total land area to 43 % in the 9-year time period (i.e., from 2001 to 2010). It also has the lowest well density of all the three regions. If total agricultural land area is considered, well density increased from 20 to 22 wells/km^2. However, if the total land area is considered, well density increased from 8 to 9 wells/km^2. The rate of increase in the number of wells in this region is the lowest out of the three regions, i.e., about 22 % in 9 years. The increase in the number of wells implies an increase in irrigation, thus leading to a higher loss of aquifer water to the atmosphere and more flushing down of agricultural chemicals to the aquifer.

The process developed for identification of wells was applied to the entire Jaffna District in the north of Sri Lanka, and groundwater budgeting was carried out for the region. Figure 5 shows the agro-well density in the Jaffna Peninsula. The analysis shows that there are 19,500 agro-wells within a total area of 913 km^2. Domestic wells are difficult to identify from this type of analysis because they are mostly covered and are too close to buildings. Assuming one domestic well per household and by counting the rooftops, it is estimated that there are approximately 58,600 domestic wells in the peninsula.

Using the methodology described above, groundwater recharge was calculated for the Jaffna region during the wet months from October to December of 2011. The rainfall obtained during the period from October 1 to

Table 3 Summary of agro-wells and area under agriculture in three pilot sites

Location	Valikamam			Medawachchiya			Kalpitiya		
Year	2003	2009	Increase # (%)	2004	2010	Increase # (%)	2001	2010	Increase # (%)
Total land area (km^2)	36.22	36.22	0 (0)	29.93	29.93	0 (0)	11.26	11.26	0 (0)
Total agricultural land area (km^2)	12.07	12.79	0.72(6.0)	9.8	8.36	−1.46 (−14.9)	4.32	4.84	0.52 (12.0)
Number of wells	796	1090	294 (36.9)	188	256	68 (36.2)	87	106	19 (21.8)
Well density (per km^2 of agricultural area)	65.9	85.2	19.3 (29.3)	19.2	30.6	11.4 (59.4)	20.1	21.9	1.8 (8.9)

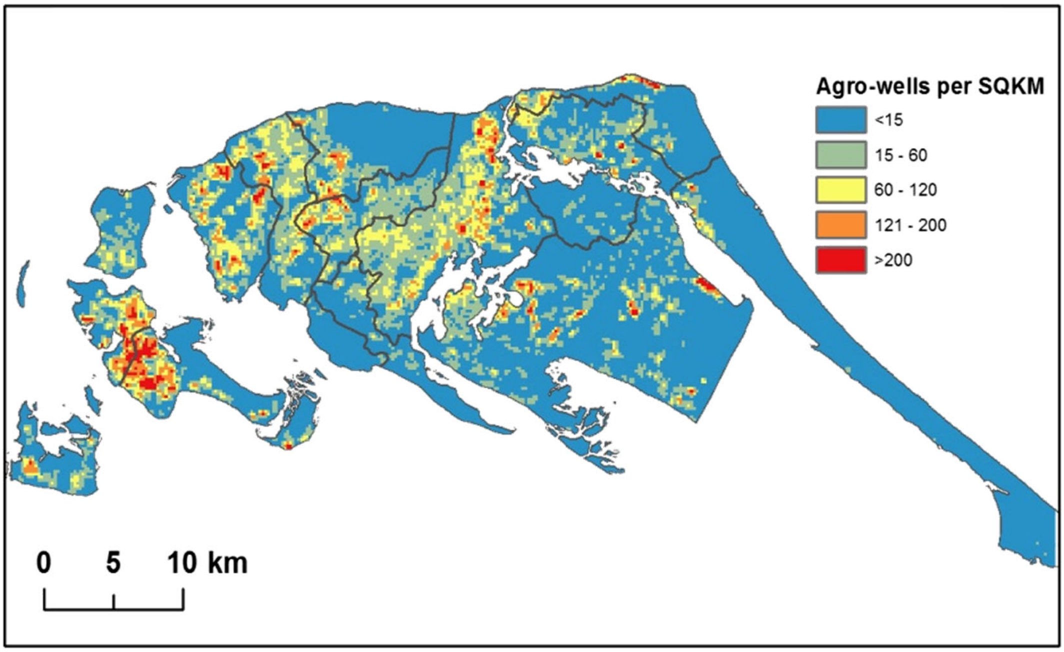

Fig. 5 Agro-well density in the Jaffna Peninsula

December 21 of 2011 was 1036 mm (301.1, 518.1, and 216.8 mm in October, November, and December, respectively), and ET was 400 mm during the same period. The value of specific yield was obtained by calibrating equation (2), so that the maximum values of gross recharge (SyΔw + ET) did not exceed the total rainfall. Thus, a specific yield value of 0.21 was found to be a reasonable match. This value falls within the range of values reported by Joshua (Joshua 1973) (reported non-capillary porosity as 20 % for Red-Yellow Latosols), Rajasooriyar et al. (Rajasooriyar et al. 2002) (assumed a value of 0.18), NWSDB (NWSDB 2006) (reported value range from 0.18 to 0.32 for various locations in Jaffna), and Thushyanthy and De Silva (2011) (reported 0.27 for Valikamam region). Spatial variation of net groundwater recharge (i.e., SyΔw) during the wet season was observed to be from 130 to 710 mm with an average of 390 mm (Table 4). This is equivalent to 12.2 to 68.9 % with an average of 37.3 % of the total rainfall obtained during the same period. Punthakey and Nimal (2006) used a calibrated model and estimated the groundwater recharge in the peninsula to be 21 % of the average annual rainfall. The gross groundwater recharge varied from 42.2 to 98.9 % with an average of 67.3 %. This indicates that about 33 % of the total rainfall results in surface runoff during the rainy season.

These values are slightly higher than the values reported by previous researchers, which may be due to the fact that these values are estimated based on wet season rainfall whereas other researchers have reported their estimates as a percentage of annual rainfall. However, these values are highly sensitive to specific yield. Also, the rainfall data used in this study was obtained from the one and only agro-meteorological station at Thirunelveli. Therefore, the spatial variability of local rainfall could not be mapped.

The maximum possible water extraction for sustainable groundwater use can be calculated by water budgeting. The calculation of groundwater balance was carried out for the entire Jaffna Peninsula using a range of groundwater recharge values. The results of the groundwater balance calculations for the entire peninsula are shown in Table 5. The analysis shows that, on average, the maximum water available for irrigation per well is a little over 4200 m^3/year to over 7600 m^3/year. Of course, the peninsula average hides a lot of spatial variation. As shown in Fig. 5, the density of agro-wells in Jaffna varies from less than 20 wells/km^2 to over 200 wells/km^2. Another point to keep in mind is that the aquifer in Jaffna is

Table 4 Net and gross groundwater recharge during the wet season (October–December, 2011)

	Location	Net recharge (SyΔw) (mm)	Gross recharge (SyΔw+Et) (mm)	Net recharge (%)	Gross recharge (%)	Depth to groundwater, July (m)	Depth to groundwater, Oct–Dec (m)
1	Mathakal	380	690	36.49	66.48	3.8	2.6
2	Uduvil	590	900	56.76	86.75	3.55	1.55
3	Jaffna	130	440	12.16	42.16	2.35	1.3
4	Neervely	450	760	42.97	72.97	1.8	0.64
5	Sankuvely	380	690	36.49	66.48	2.5	1.4
6	J/173	570	880	54.73	84.73	2.97	1.62
7	Sankarathai	500	810	48.65	78.65	2.4	1.3
8	Elalai	290	600	28.38	58.38	4.45	3.55
9	Kantharodai	500	810	48.65	78.65	2.5	1.4
10	Thirunelveli	530	840	50.68	80.67	3.3	2.25
11	Jaffna	400	710	38.51	68.51	3.25	1.95
12	Jaffna	630	940	60.81	90.81	3.3	1.6
13	Puttur	290	600	28.38	58.38	3.06	2.16
14	Siththankeni	530	840	50.68	80.67	2.6	1.55
15	Moolai	710	1020	68.92	98.92	3.45	1.75
16	Navaly	630	940	60.81	90.81	3.35	2.05
17	Manipay	320	630	30.41	60.4	6.15	5.5
18	Alaveddy	500	810	48.65	78.65	2.6	1.5
19	Irupalai	250	560	24.32	54.32	1.4	0.7
20	Vaddukoddai	380	690	36.49	66.48	1.2	0.6
21	Kopai	230	540	22.3	52.29	7.05	6.15
22	Neervely	290	600	28.38	58.38	4.85	4.1
23	Neervely	340	650	32.43	62.43	5.25	4.7
24	Punnalaikadduvan	320	630	30.41	60.4	4.4	3.65
25	Mallakam	420	730	40.54	70.54	6.3	5.5
26	Puttur	290	600	28.38	58.38	5.67	4.87
27	Kopai	340	650	32.43	62.43	7	6.3
28	Kondavil	290	600	28.38	58.38	7.3	6.4
29	Thirunelveli	360	670	34.46	64.46	9.6	8.95
30	Urumpirai	320	630	30.41	60.4	5.9	5.05
31	Urumpirai	340	650	32.43	62.43	5.1	3.9
32	Urumpirai	320	630	30.41	60.4	5	4.25
33	Pandatharippu	440	750	42.57	72.56	2.1	1.05
34	Kokuvil	350	660	33.45	63.44	7.9	7.13
35	Inuvil	270	580	26.35	56.35	6.3	5.45
36	Chankanai	420	730	40.54	70.54	5.9	5.1
37	Ilavalai	400	710	38.51	68.51	3.8	2.75
38	Alaveddy	400	710	38.51	68.51	6.4	5.65
39	Thellipalai	270	580	26.35	56.35	3.1	2.35
40	Punnalaikadduvan	340	650	32.43	62.43	4.9	3.8
41	Neervely	250	560	24.32	54.32	6	4.3
42	Urumpirai	320	630	30.41	60.4	6.2	5.25

Table 4 (continued)

	Location	Net recharge (SyΔ*w*) (mm)	Gross recharge (SyΔ*w*+Et) (mm)	Net recharge (%)	Gross recharge (%)	Depth to groundwater, July (m)	Depth to groundwater, Oct–Dec (m)
43	Neervely	380	690	36.49	66.48	4	3.1
44	Maruthanamadam	360	670	34.46	64.46	5.6	4.85
	Average	390	700	37.26	67.25	4.45	3.44
	Minimum	130	440	12.16	42.16	1.20	0.60
	Maximum	710	1020	68.92	98.92	9.60	8.95

not continuous, which implies that the same well density in different regions may have different impacts on groundwater budgeting. For this type of analysis, a detailed site-specific study may need to be conducted.

Similar groundwater budgeting was carried out within the administrative boundary (i.e., DS level) in Jaffna. There are 13 DS divisions in Jaffna, out of which 11 are on the mainland and are considered in this budgeting exercise. The results of this exercise are shown in Table 6. In Table 6, the per capita domestic water needs, the rate of evaporation loses from the wells, and the water lost to sea are same as those considered for Table 5. Water available for pumping is calculated as the water left from groundwater recharge after domestic needs are met and water lost due to evaporation and loss to sea is accounted for. It can be seen that there is a wide variation in the groundwater available per well in different regions, which ranges from 45,155 m^3 (high of 80,149 m^3) per well in Vadamaradchi East to about 2215 m^3 (high of 4030 m^3) per well in Valikamam East. Assuming that the pumps can discharge water at the rate of 3500 L (or 3.5 m^3) per hour, they are operated for 300 days in a year, and if the resources are equitably distributed, each pump in the Valikamam East region will not be able to discharge water more than 2.1 to 3.8 h daily. A similar analysis shows that in Valikamam South, Valikamam Southwest, and Valikamam West, a pump can be operated less than 3 h (or 5 h, if we assume a high groundwater recharge rate) daily for equitable distribution.

Table 5 Annual groundwater balance for the Jaffna Peninsula

Item	Quantity (Mm^3)
Total groundwater recharge[a]	335.98 (246.51–437.33)
Total water needs for domestic purposes[b]	7.70
Water lost due to evaporation from wells[c]	2.72
Water lost to the sea[d]	162.78 (118.044–213.45)
Water available for pumping[e]	113.95 (82.631–149.42)

Mm^3 million cubic meters

[a] Based on groundwater recharge of 270 mm per year (Punthakey and Nimal 2006) and 37.3 % of rainfall as calculated in this research

[b] Based on average household size of four people (Household Income and Expenditure Survey—2009/10. 2011. Department of Census and Statistics, Ministry of Finance and Planning, Sri Lanka) and water needs per person estimated at 90 L/day

[c] Considering class A pan evaporation as 6.00 mm/day (Panabokke 1996) and average diameter of a well as 4.5 m

[d] Assuming 50 % of groundwater is lost to the sea (Panabokke and Perera 2005)

[e] Assuming 70 % of the remaining water can be pumped

Table 6 Groundwater budgeting at Divisional Secretariat (DS) level in the Jaffna Peninsula

	Jaffna	Nallur	Thenmaradchi (Chavakachcheri)	Vadamaradchi East	Vadamaradchi North (Point Pedro)	Vadamaradchi Southwest
Total groundwater recharge (Mm^3)[a]	5.37 (3.94–6.99)	12.22 (8.96–15.9)	81.29 (59.64–105.81)	48.06 (35.26–62.56)	14.68 (10.77–19.11)	29.04 (21.3–37.79)
Total water needs for domestic purposes (Mm^3)	0.62	0.75	1.06	0.02	0.77	0.77
Water lost as evaporation (Mm^3)	0.16	0.21	0.38	0.02	0.23	0.24
Water lost to the sea (Mm^3)[a]	2.3 (1.58–3.11)	5.63 (4.01–7.48)	39.93 (29.1–52.19)	24.01 (17.61–31.26)	6.84 (4.89–9.06)	14.01 (10.15–18.39)
Water available for pumping (Mm^3)[a]	1.61 (1.11–2.17)	3.94 (2.8–5.23)	27.95 (20.37–36.53)	16.81 (12.33–21.88)	4.79 (3.42–6.34)	9.81 (7.1–12.87)
Groundwater available per agro-well (m^3)[a]	61,803 (42,543–83,619)	15,402 (10,954–20,440)	10,193 (7430–13,323)	61,564 (45,155–80,149)	6395 (4568–8465)	9008 (6523–11,823)
Number of hours per day[a]	58.86 (40.52–79.64)	14.67 (10.43–19.47)	9.71 (7.08–12.69)	58.63 (43–76.33)	6.09 (4.35–8.06)	8.58 (6.21–11.26)

	Valikamam East (Kopay)	Valikamam North	Valikamam South (Uduvil)	Valikamam Southwest (Sandilipay)	Valikamam West (Chankanai)
Total groundwater recharge (Mm^3)[a]	38.42 (28.19–50.01)	20.42 (14.99–26.58)	13.84 (10.15–18.01)	18.8 (13.8–24.48)	27.12 (19.9–35.3)
Total water needs for domestic purposes (Mm^3)	1.13	0.26	0.46	0.81	0.95
Water lost as evaporation (Mm^3)	0.45	0.1	0.17	0.28	0.33
Water lost to the sea (Mm^3)[a]	18.42 (13.31–24.22)	10.03 (7.31–13.11)	6.61 (4.77–8.69)	8.86 (6.35–11.69)	12.92 (9.31–17.01)
Water available for pumping (Mm^3)[a]	12.9 (9.31–16.95)	7.02 (5.12–9.18)	4.63 (3.34–6.09)	6.2 (4.45–8.18)	9.04 (6.52–11.91)
Groundwater available per agro-well (m^3)[a]	3066 (2215–4030)	7880 (5743–10,300)	3547 (2558–4667)	3382 (2425–4465)	3929 (2831–5172)
Number of hours per day[a]	2.92 (2.11–3.84)	7.5 (5.47–9.81)	3.38 (2.44–4.45)	3.22 (2.31–4.25)	3.74 (2.7–4.93)

Mm^3 million cubic meters

[a] Values in parenthesis give the range based on high and low values of groundwater recharge in each DS

The groundwater extraction from the wells also needs to be constrained to control the movement of the saline water interface. The high density of wells is leading to higher fluctuation of groundwater table. Figure 6 shows the groundwater table fluctuation in 2011. When overlain over the well density map, it can be seen that regions with higher well density also have higher water table fluctuation. The higher water table fluctuation impacts the salinity of groundwater in the region. Figure 7 shows the mapping of electrical conductivity (EC) in the Jaffna peninsula (based on the study conducted by (Sutharsiny et al. 2012)) for different months of the year. The EC, which can be taken as a proxy of salinity in the groundwater, is restricted to the coastal areas for the months of January, March, and April but spreads rapidly inland by July and even more in October. In the region, since the rainy season is from October to December, groundwater recharge pushes the saline water, which is found only near the coast by the end of the rainy season (January). As groundwater is extracted to meet the agricultural water demand in the region, the saline water gets pushed more and more inland. One of the main factors responsible for the high rate of extraction is the large

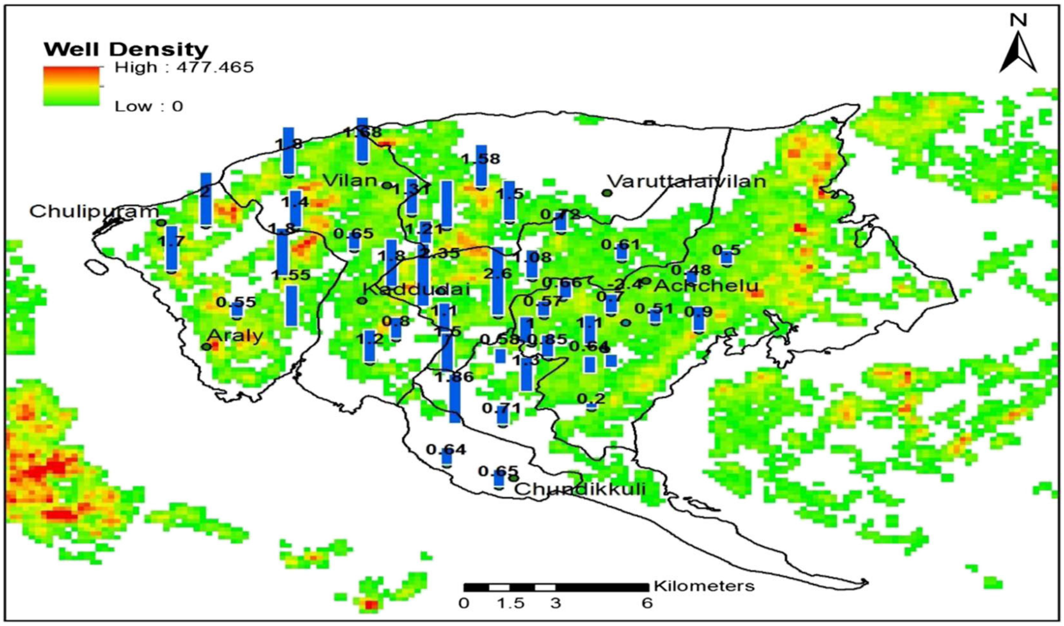

Fig. 6 Annual water table fluctuation in 2011 in relation to well density. The *relative height of bar* shows the fluctuation level, and the *numbers* show the actual fluctuation in meters

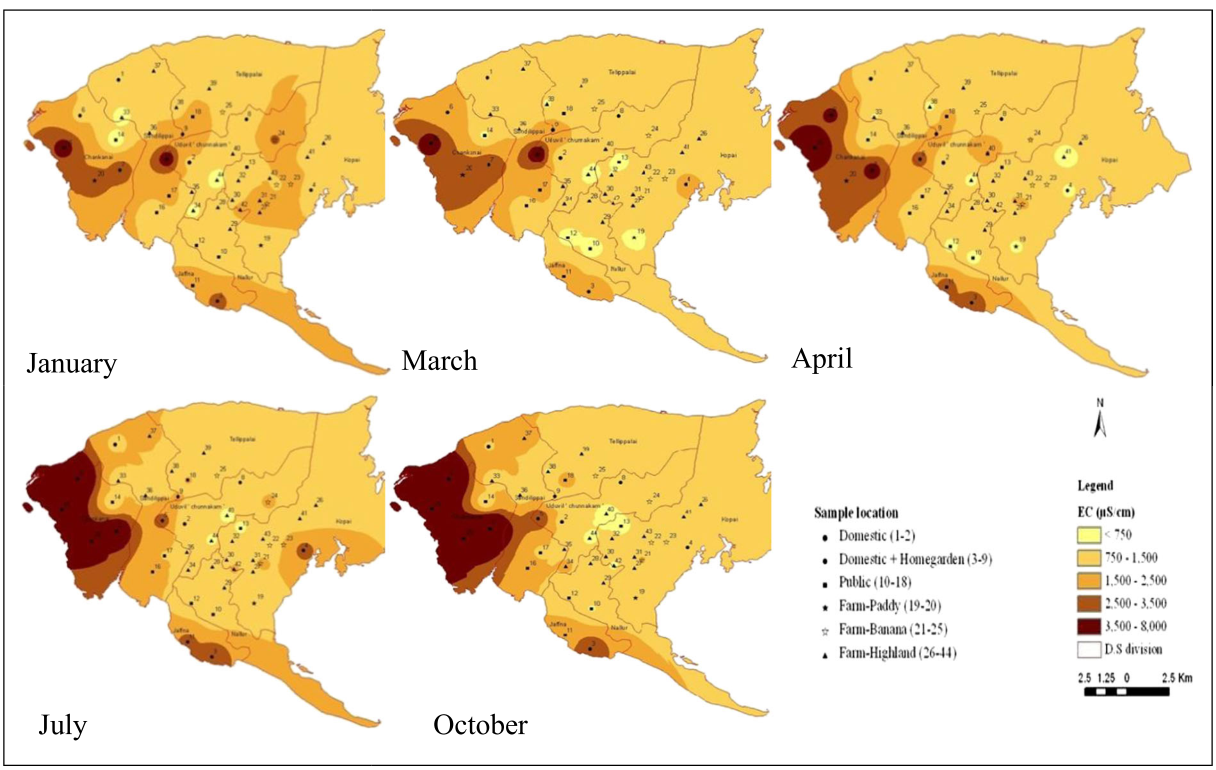

Fig. 7 Electrical conductivity (EC) mapped in 2011 for the different months in the Jaffna Peninsula

well density in that region. As can be seen in Figs. 6 and 7, the coastal area, where salinity is higher, has a well density ranging from 60 wells/km^2 to over 200 wells/km^2 and annual water table fluctuation from 0.55 to 2 m.

Conclusions

Groundwater has been mostly ignored from a water management perspective. In this paper, groundwater issues in the dry zone of Sri Lanka are discussed. The issues can be broadly classified as management-related or governance-related. One of the major factors common to such issues is the lack of information on groundwater, as it is difficult to get an inventory of individual wells. Easy and comprehensive access to information can help in better management of, and policy development for, groundwater. Remote sensing and high-resolution images are good tools that can be used in policy and decision making and can be effectively used to develop science-based management practices.

It has been shown how high-resolution images can be used to look at the progression of wells over time. The identification of wells can also help in defining the “hot spots” within a region, i.e., the areas where the well density is very high. This would eventually lead to better governance, as the initiatives can be focused on these highly stressed areas. Comparing three different regions, it was found that over the last decade, the well density is on the rise in all the regions of the dry zone. This paper shows that this type of spatial identification of wells can also assist in conducting a quick groundwater balance, which can help in developing sustainable groundwater harvesting policies. Groundwater budgeting carried out in Jaffna shows that, in some regions, based on the current well density and even with average rainfall, less than 3 h of pumping should take place daily in order to achieve sustainable use of groundwater. It would be even lower in the dry years. Other factors such as water quality need to be considered too. The analysis also shows the relevance of spatial scales when looking at groundwater issues. There is a wide variation in the well density within the Jaffna Peninsula.

This work can be further extended to study water quality issues. Groundwater quality maps can be developed based on the water quality data collected from sample wells and by using appropriate interpolation techniques. Such water quality maps, when overlaid over the agro-well distribution map, can readily provide an inventory of wells with water quality issues. One such example, where EC is mapped using data collected from the water samples in 44 spatially distributed wells, is shown here. This too can help speed-up policy implementation in targeted areas.

It is suggested that such well identification exercises should be conducted in all the areas with high levels of groundwater use and future groundwater policies be developed based on these maps.

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