Chapter 44
The New Water: Opportunities and Challenges of the Rise to Prominence of Groundwater in Sri Lanka in the Face of Socioeconomic and Climatic Change

Sanjiv de Silva, Mohamed Aheeyar, Indika Arulingam and Herath Manthrithilake

Abstract Overall high annual precipitation in Sri Lanka belies significant spatial and temporal variation in surface water availability. The 'dry zone' comprising two-third of Sri Lanka's land area receives significantly less rainfall and has high precipitation rates and a five-month dry season. Nevertheless, these regions account for the majority of rice production, the staple crop, thanks largely to the ancient hydraulic civilization based on networks of rainwater harvesting (irrigation) tanks. This manipulation of surface water resources including modern surface irrigation schemes continues to form the backbone of dry zone farming. Groundwater irrigation has remained in the shadows except in the North where surface flows are absent. This scenario is now changing as population growth; poorly maintained infrastructure; commercial agriculture; sectoral competition for water and climate change combine to exert severe pressure on surface water resources. Since the dry zone is also home to a large number of Sri Lanka's poor households, and a close association exists between high poverty clusters and access to irrigation, the implications of water insecurity for a range of poverty indicators are clear. Not surprisingly, these pressures have prompted an increasing recourse to groundwater in several parts of the dry zone, as governments and farmers recognize the imperative to increase agriculture output, promote crop diversification, and improve agrarian incomes. Yet, with limited groundwater potential, limited detailed knowledge of this resource, and under-developed groundwater-oriented institutions, it is far from certain whether future groundwater exploitation can steer away from anarchy.

Keywords Sri Lanka · Groundwater · Water governance · Climate adaptation Resilience

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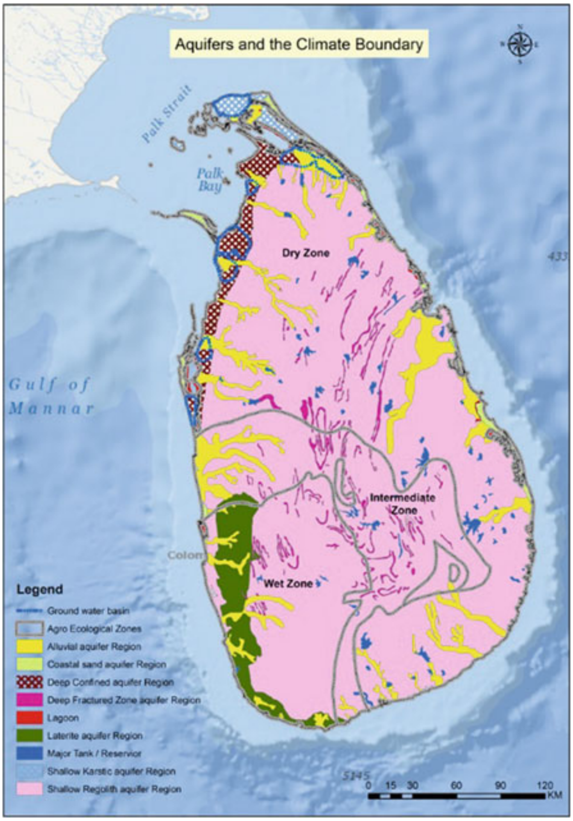

Fig. 44.1 Aquifers in Sri Lanka

44.1 Introduction

44.1.1 Groundwater in the Overall Water Context

An examination of the status and recent emergence to prominence of groundwater in Sri Lanka needs to be framed by the historical context of water use and its management in Sri Lanka (Chap. 1, Fig. 1.1), which has been dominated by an overall high annual precipitation level. At face value, this has created a perception of water security by virtue of ample surface water flowing in Sri Lanka's 103 major rivers which cover 90% of the islands land extent (Irrigation Department[1]). However, that this belies significant spatial and temporal variation is clear from the extensive hydrological civilization based on man-made rainwater storage and water conveyance for irrigation developed by the ancient kingdoms since at least

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[1] http://www.irrigation.gov.lk/index.php?option=com_content&view=article&id=340&Itemid=245&lang=en. As defined under the Agrarian Services Act, No. 58 of 1979.

300 B.C. (Brohier 1935). This infrastructure, ranging from small village tanks to much larger tanks or reservoirs that supply entire regions, is a direct response to the natural segmentation of the island into three climatic zones based on rainfall (Fig. 44.1), where the 'dry zone' comprising roughly two-third of the land area receives on average less than 1,750 mm of rainfall (Punyawardane 2008), of which very little falls during the long dry season between May and September. This contrasts with an annual average evaporation rate of 1,700–1,900 mm (Panabokke et al. 2002) which makes clear that water in the dry zone is far from being abundant. Thus, the majority of the estimated 30,000 tanks (functioning and abandoned) of varying size are also distributed across this dry zone landscape (Mendis 2003). Between 12,000 and 16,000 of these functioning tanks are 'small' in scale (less than 80 ha[2]) according to Panabokke (2009) and provide water at village scale, while most dry zone villages possess several such tanks. As noted by Brohier (1935), some of these tanks have been in continuous operation for over 2,000 years. Another important feature is the 'cascade' approach to the use of many of these tanks, whereby a series of tanks are connected within a micro-(or meso-) catchment for storing, conveying, and using and reusing water. These cascades further represent a distinct small watershed or meso-catchment ranging from 13 to 26 km^2 in extent (Madduma Bandara 1995). These investments in water storage are intertwined with paddy cultivation as the mainstay of agrarian livelihoods especially in the dry zone, with typically one major rainfed (*maha*) crop and one surface irrigated crop in the dry (*yala*) season, traditionally utilizing water stored in the irrigation tanks.

Annual total freshwater withdrawals in Sri Lanka were estimated at 13 billion m^3 in 2014 according to the World Bank (2014), where irrigation for agriculture accounted for 87%, of which rice accounted for 82%. Employing nearly 30% of the total labor force, the agriculture sector is also an important foreign exchange earner, accounting for about 30% of the total earnings. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

44.1.2 Groundwater Resources

This manipulation of surface water resources through irrigation tanks continues to form the backbone of dry zone farming, while its prevalence in the national consciousness contributes to a hydraulic culture focused almost exclusively on surface water resources. Consequently, although Sri Lanka has six types of aquifer systems across its 65,000 km^2 land area (Fig. 44.1), and a variety of geological and hydrogeological settings, extraction of groundwater for agriculture has traditionally been limited to the northern and eastern provinces which lack perennial surface water resources. In the Jaffna Peninsula that forms the northern part of the island, for

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[2] As defined under the Agrarian Services Act, No. 58 of 1979.

instance, groundwater use for domestic and agriculture purposes, has occurred for nearly 1,500 years (Panabokke and Perera 2005). Groundwater has however been used for drinking and other domestic purposes throughout the country and is the only source of domestic water in a number of districts, including Jaffna, Vavuniya, Batticaloa, and Mannar (Villholth 2013). In fact, despite this secondary role of groundwater in irrigation, it is estimated that over 55% of Sri Lanka's population relies on groundwater for their daily domestic needs (Herath 2006). The main types of both shallow and deep groundwater aquifers identified (Panabokke 2003) are: (1) Shallow unconfined karstic aquifers; (2) Deep confined sandstone and Miocene limestone aquifers; (3) Shallow quaternary unconfined coastal sand aquifers; (4) Alluvial aquifers of variable depth; (5) Lateritic (cabook) aquifers, and (6) Regolith aquifers of the hard-rock region. Investigations have shown that groundwater in the regolith aquifer occurs in two main forms, namely (i) the shallow regolith aquifer and (ii) the deeper fracture zone aquifer. The deep fracture zone aquifer occurs at random at depths of 30–40 m in the hard-rock metamorphic regions according to the presence of lineaments in the basement rocks. Each of these aquifers has distinct characteristics (Annex). Overall, the groundwater potential of Sri Lanka is lower compared to surface water resources. Total estimated groundwater potential is 7.8 billion m^3 per annum (UNEP 2005), equal to about 15% of the country's surface water resources (Climate Change Secretariat 2010), with rainwater as the main source of the recharge. According to WRI (2003), the amount of groundwater available in the island is 8 km^3, with another 7 km^3 shared between surface and groundwater.

Even among the six aquifers, about 90% of the island's land mass relies on the regolith (fractured crystalline) aquifer for groundwater supply, while the remaining groundwater supply is sourced from confined sedimentary type aquifers located mainly in the north and northwestern provinces of the country (Panabokke 2003). Yields of the regolith aquifer systems are reported to be 1–4 L/s (Hapugaskumbura 1997), indicating the overall limitation to groundwater use in a significant portion of the country. Shallow aquifers play an important role in providing domestic supplies from traditional wells of between 6 and 9 m depth, and also in discharging water to rivers and other water bodies during low flow periods, while supporting wetlands and native vegetation (Panabokke and Perera 2005).

44.1.3 Emerging Water Stress, Socioeconomic Change, and the Rise of Groundwater in the Dry Zone

Despite Sri Lanka being categorized as a middle-income country, 6.7% of its population of 20.48 million was estimated to be living below the poverty line in 2012/13 (World Bank 2016a). Figure 44.2, adapted from a mapping of households below the poverty line by Amarasinghe et al. (2005), makes clear that a large number of these poor households remain within the dry zone. The same authors also found a close association between high poverty clusters and areas lying outside of

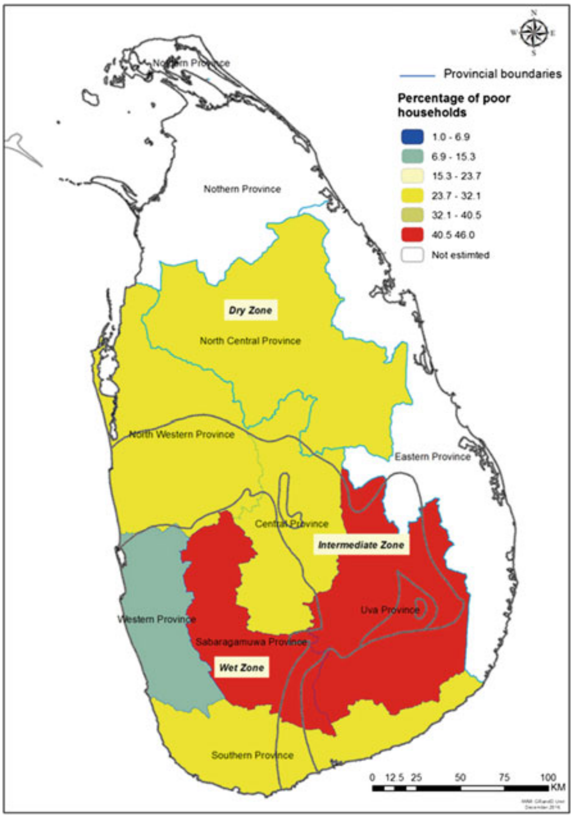

Fig. 44.2 Distribution of poor households in Sri Lanka. *Source* Adapted from Amarasinghe et al. (2005)

modern irrigation schemes, indicating the material influence of access to irrigation to the incidence of poverty. A number of factors can be attributed in explaining this finding, including the gradual loss of efficacy of the village tanks, a number of which are abandoned due to poor maintenance, while others' water-holding capacity has diminished due to siltation (Panabokke 2009). This diminished storage capacity contrasts with growing water demand in agriculture, industry, and urban sectors, and consequently, unless served by a modern irrigation scheme, many dry zone villages can in fact only cultivate rainfed rice, with agriculture in the dry season limited to slash and burn subsistence highland cultivation. This inability to generate economic returns during almost half of the year remains a significant challenge to agrarian communities, especially as Sri Lanka rapidly transitions to a middle-income country driven by a market economy that grew by an average of 6.4% between 2010 and 2015 (World Bank 2016b) concurrently consolidating a monetized market-based society. This, along with population growth, now places increasing pressure on agriculture (and water resources) to satisfy both domestic and export markets as well as to generate economic values that can meet the growing material aspirations of especially the youth.

Intensifying these anthropogenic drivers are the impacts of climate change. Although the predicted impacts of climate change in Sri Lanka vary according to the models used, Ahmed and Suphachalasai (2014) conclude that under a business-as-usual scenario, the impact would be an annual loss of 1.2% of GDP by 2050, which would increase to 6.5% in the long term. Impacts on agriculture predict both increases and decreases in yield, depending on the location of production and time-scale. Of particular relevance is Seo et al.'s (2005) prediction that changes to net income from rice production could decrease by 27–46%. Decreased precipitation in the central highlands is also expected to lead to a change in the catchment for the multipurpose Mahaweli Complex, by far the largest investment in providing dry season irrigation to paddy farmers in the dry zone (North Central Provinces). Consequently, due to the combined impact of reduced precipitation, increased potential evapotranspiration and rainfall seasons that end earlier, irrigation water requirements in this area are expected to increase by up to 23% (De Silva et al. 2007; Eriyagama et al. 2010). Since 71% of agriculture land holdings in Sri Lanka are less than one hectare, where surplus production is not common, smallholder farmers with land that is rainfed or irrigated from minor tanks are considered to be particularly vulnerable to the impacts of climate change (Esham and Garforth 2013). With respect to groundwater resources, Eriyagama et al. (2010) note that this has been the subject of only limited studies, even though most available sites for surface water storage are exploited, and previously under-developed groundwater resources may become increasingly important going into the future. Overall, the impact of climate change on the water sector in Sri Lanka will be felt more strongly by those dependent on the agriculture sector for livelihood and food security, with parts of the dry zone considered as some of the most at-risk areas (Eriyagama et al. 2010). This culmination of pressures has prompted recourse to groundwater in several parts of the dry zone, as both governments and farmers recognize the imperative to increase agriculture output, promote crop diversification, and improve agrarian incomes. These are discussed in the next section.

44.2 Current Trends in Groundwater Use

As already noted, increasing pressures on surface water resources are resulting in a growing demand for groundwater to meet domestic water needs, small-scale irrigation, industrial uses, and the service sector. This has led to groundwater extraction at an accelerated pace over the last few decades for the cultivation of high-value cash crops and other development activities that now exert considerable pressure on the shallow and ephemeral nature of groundwater resources in the country. The Government of Sri Lanka was instrumental in promoting groundwater irrigation through the National Agro-well Program initiated in the late 1980s to increase the income levels of rainfed farmers living in the dry zone through high-value crop cultivation. These emerging trends in groundwater use are discussed below.

44.2.1 Agricultural Use

Groundwater is cheap and an easily accessible source of irrigation for both poor and rich farmers, where pump ownership means access and use is controlled by the users themselves. The adoption of low-cost technologies for accessing groundwater (open/tube wells and pumps) has allowed farmers to grow high-value crops, minimize the risks posed by drought, and enhance income from higher cropping intensities. Income received by the groundwater irrigation in Sri Lanka is consequently 4–5 times higher compared to other South Asian countries due especially to diversification to high-value cash crops. For example, one acre (0.4 ha) of land cultivated with cash crops under agro-wells in Anuradhapura has provided a net income equivalent to the income of 5–15 acre (2–6 ha) of irrigated paddy (Shah 2013). Not surprisingly, extraction of groundwater for cash crop production has been increasing rapidly during the last two decades in the dry zone areas of Sri Lanka (IWMI 2003; Athukorala and Wilson 2012). The highest number of agro-wells is located in the regolith aquifer, which is replenished by the extensive irrigation tank cascade system functioning as recharge structures. Coastal sand aquifer areas in the northwestern and northeastern regions are extensively used for intensive agriculture in an area of around 125,000 ha (Panabokke and Perera 2005). While IWMI (2003) estimated the total number of agro-wells in the dry zone to be around 50,000 in the year 2000, Shah (2013) expects this number to have increased to 200,000–250,000 by 2013. This growth in groundwater used for agriculture also represents the evolution of a number of enabling factors such as the availability and affordability of pumps and machinery for well construction on the supply side, and several facets of the country's economic development that has generated the market and other conditions favorable for diversification of farming from the primary paddy crop to parallel production systems-based around high-value non-paddy crops (NPCs). These are demonstrated and discussed in the case studies presented in Sect. 44.3 that represent the major forms of emerging groundwater use in agriculture.

44.2.2 Industrial Uses

Groundwater is the primary source of water for export promotion zones, industrial estates, and small and large enterprises. For example, only a part of the water requirement of the 98 factories established within the Katunayake Export Processing Zone is supplied from surface water sources and the rest of the water requirement is fulfilled by groundwater obtained from 44 shallow and deep tube wells. These wells supply an estimated 3,000 m^3 per day. The tourist hotels in the Katunayake area and most of the private establishments located along the coastal belt also rely on this aquifer (Wijesekara and Kudahetti 2011), which is a growing industry especially after the cessation of the civil conflict in 2009. This is most likely to continue in the current context due to the cheapness of groundwater and the lack of potable water to meet the growing demand.

In the southwestern lateritic aquifers, high rates of extraction for industrial estates, the tourism industry, urban housing schemes, and bottled water projects exert considerable pressure on the groundwater resource (Panabokke and Perera 2005). Many industries have their own wells which, whether or not registered, are not monitored in terms of water extracted. Multiple industries, especially in the metropolitan area of Colombo and in stretches of the southwestern coast, take advantage of deep groundwater resources from self-managed wells.

44.2.3 Domestic Use

Groundwater is the preferred low-cost source of water for most rural and semi-urban domestic water supply (Table 44.1). The Department of Census and Statistics (2012) estimates that nearly 54% of the population in Sri Lanka was dependent on groundwater for drinking needs in 2011. This reflects the approximately 400 million m^3 households directly withdraw from domestic wells and tube wells. This figure does not reflect the populations covered by groundwater-based pipe-borne state-sponsored and other water supply schemes which account for nearly 30% of drinking water supply schemes in the country according to Panabokke and Perera (2005). The same authors therefore estimate that the total contribution of groundwater to domestic water supply may be as high as 80%. Moreover, this excludes the groundwater used as a supplementary source by households that receive pipe-borne water supplies (Herath 2006).

This dependence on groundwater for rural and semi-urban water supplies has spawned nearly 30,000 tube wells in various parts of the country (Prematilaka 2011) constructed during the last three decades by various organizations such as NWSDB, water resources board (WRB), foreign funded-projects, and private sector organizations. These wells are of various types, including hand pump wells for the rural populations, and several deep wells (Prematilaka 2011). There are also some shallow open dug wells constructed by local organization and individuals for which no reliable records are available. This dependence on groundwater in the domestic

Table 44.1 Available estimated annual groundwater withdrawals for domestic water supply

Users	Function	Total annual withdrawal (m^3)
NWSDB	Pipe-born domestic water supply	1,908[a]
Households	Primary source of domestic water supply	400 million
Households	Supplementary to surface drinking water schemes	Unknown

[a] Prematilaka (2011)

Source Compiled by authors from multiple sources sector is likely to increase in view of recent droughts where some regions such as Humbantota and Monaragala districts (Southern and Uva Provinces, respectively) run out of surface water supplies. This has prompted the NWSDB to look at the potential for supplementing domestic supplies from aquifers during drought periods (K. M. Premathilake,[3] pers. com.).

44.3 Case Studies Representing Emerging GW Use in the Agriculture Sector

44.3.1 Emerging Uses Outside of Surface Systems

44.3.1.1 The Evolution of High-Value Commercial Cropping in Kalpitiya

Kalpitiya is a low-lying sandy peninsula of 160 km^2 situated in the Northwestern Province of Sri Lanka (Fig. 44.3). The area is classified as part of the dry lowland (DL_3) agroecological zone with an average annual rainfall of about 900 mm. This rainfall is however limited to 2–3 months, with about 280 days in a year passing without rainfall. Available groundwater consists of a freshwater lens at 1–3 m depth floating over brackish water. The sandy aquifer is recharged by both direct infiltrations from the northeast monsoon and return irrigation flows.

With no surface irrigation or rainfed cultivation, farmers in Kalpitiya are completely dependent on groundwater. Before the 1990s, shallow dug wells were the main source of irrigation water. Each well costs approximately LKR 50,000–75,000 (USD 394–590). Groundwater use was effectively self-regulated as farmers used to irrigate manually with buckets, and any changes occurred in the water level were visible in the open dug wells. Manual irrigation required four to five person-days to irrigate one acre (0.4 ha), which limited the extent cultivated by a farmer from 0.1 to 1 ha. This changed with the introduction of energized water pumps in the mid-1980s and triggered substantial shifts in cultivation patterns and crop intensification. These pumps and hoses to convey the water to fields were adopted rapidly as this reduced the labor demand for irrigation by over 50%. This reduced dependence on labor also enabled an expansion in cultivation area. Further technological innovation occurred after 2005 with the gradual increase in labor cost, whereby, despite the labor savings from pumps, the average cost of irrigation accounted for nearly 35% of the total production cost (Melvani et al. 2006). Farmers therefore developed user-friendly and cost-effective local sprinkler irrigation systems. With the adoption of local sprinkler technology, crop intensification and commercialization of cultivation further expanded as this technology reduced the labor requirement to 0.5 person-days per acre (1.25 person-days per ha). Almost

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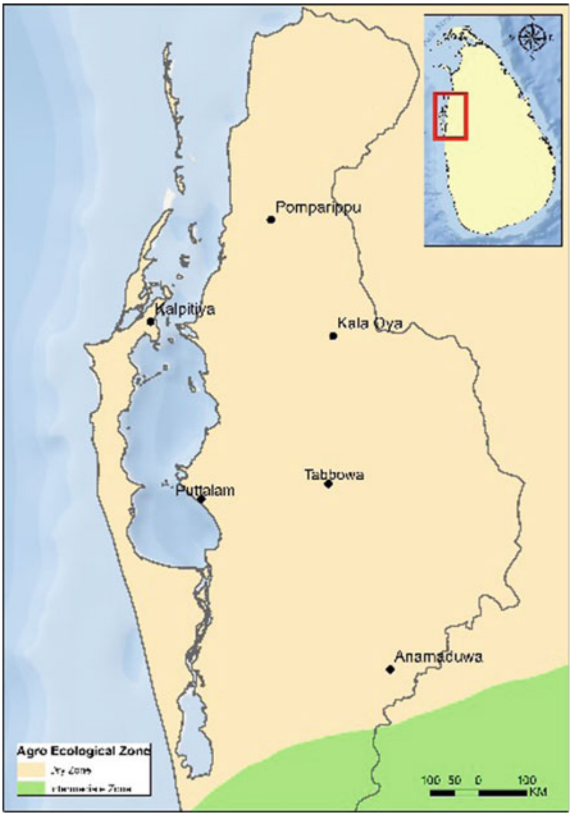
[3] Manager (Groundwater Studies), National Water Supply and Drainage Board.

Fig. 44.3 Location of the Kalpitiya peninsula



all the farmers involved in cash crop cultivation have adopted this technology and have also expanded the area cultivated.

To support the sprinkler irrigation systems, farmers needed two to three extra wells per hectare to irrigate the expanded land, and by 2010 there were over 1,500 farmers using more than 4,500 tube wells/agro-wells (Hydrosult Inc. 2010). The construction of additional wells was simplified with the cost-effective and easy-to-construct tube well technology. The construction cost of a 10.5 m deep and 15 cm diameter tube well was only LKR 12,500–15,000 (USD 98–118) at 2012 prices, only about 20% of the cost of an agro-well. Two or three tube wells located about 8 m apart are connected to a single centrifugal pump to irrigate one hectare. These pumping arrangements are similar to the skimming of wells used in Pakistan to draw water from relatively shallow, freshwater lenses overlaying saline water at greater depths, thereby avoiding saltwater intrusion (Sufi et al. 1998; Saeed et al. 2002; Saeed and Ashraf 2005). In Kalpitiya, the group of wells reduces drawdown and enables the pump to maintain adequate water pressure to operate the sprinklers. Shah (2009) described the unregulated proliferation of wells, such as those seen in Kalpitiya, as ‘anarchy.’ An unfortunate side effect of the transition from agro-wells to tube wells is that the water table has become invisible to the users, eroding an important component of the earlier self-regulation.

Despite the general and repeated failure of formal promotion of micro-irrigation across the country, this was not the case in the Kalpitiya Peninsula, where the sprinkler technology has been adopted and spread quickly in this groundwater-based agricultural economy during a short period of 10 years. It continues to expand and be adopted. The adoption of sprinkler irrigation enabled the majority of farmers to cultivate three or more crops each year, resulting in an increase in the net sown area, net irrigated area, cropping intensity, and irrigation intensity. Crop intensification, land expansion, and crop commercialization accomplished through the groundwater-based sprinkler irrigation technology has increased agricultural income substantially, providing a net income per season in the range of LKR 300,000 (USD 2,360) to LKR 1,000,000 (USD 7,875) from a single hectare of cultivation. These impacts are importantly attributed to groundwater and its buffering role in food production and agrarian livelihoods as seen across the world where groundwater protects against droughts helps intensify cropping and allows farmers to diversify to high-value crops (Shah 2014).

Success, however, has often sown the seeds of trouble as over-exploitation and ineffective governance given diffused pump ownership, have led to declining groundwater tables (Shah 2014). The low water-holding capacity of Kalpitiya's sandy soils force farmers to apply more water and/or irrigate more frequently. This also unintentionally pollutes the aquifer with irrigation return flows carrying agricultural pollutants such as fertilizer and pesticide residues (Lawrence and Kuruppuarachchi 1986; Kuruppuarachchi and Fernando 1990, 1999; Matara Arachchi et al. 2014; Melvani et al. 2006). In addition, heavy abstraction from this shallow coastal aquifer may result in saline water intrusion, particularly during dry months.

Attempts to indirectly regulate groundwater use through the introduction of micro-irrigation technologies has produced substantial benefits for individuals by increasing production and income. However, the sustainability of these benefits is at risk as a result of the negative consequences of over-extraction and pollution of the resource, which are occurring due to the absence of effective governance arrangements to regulate the use of the aquifers. In the absence of any formal regulation from government agencies or self-regulation of abstraction, use of this common property resource for individual benefit is causing considerable damage to the groundwater asset base. A concerted effort is required to help communities to assess and monitor the status of groundwater regularly at the village level. Agencies must use relevant knowledge and scientific principles to help estimate the available water for each crop season. Kalpitiya case suggests that the groundwater intervention focus so far has been largely on 'resource development,' and not on 'resource management.' This has witnessed the problems of excessive drawdown in the fragile environment, and the deterioration of groundwater quality.

44.3.1.2 Agro-Well-Driven Cultivation of High-Value OFCs in the North Central Province

In 1989, the government started to provide subsidies to construct agro-wells (typically 20 ft in diameter and between 20 and 30 ft deep) in parts of Sri Lanka's dry zone through the National Agro-well Program to address persisting poverty by stimulating dry season cultivation which historically suffered from the long dry season, especially in areas unserved by surface water irrigation schemes. Households in these areas remained poor, with few employment opportunities outside of paddy cultivation. Through the Agro-well Program a few households in several villages in Anuradhapura District (Fig. 44.4) in the North Central Province (NCP) received a 50% subsidy for digging agro-wells and the purchase of diesel pumps. The program coincided with the groundwater-driven green revolution that made pumping technologies available and affordable. With each agro-well irrigating up to one acre, groundwater was pumped from the shallow regolith aquifer lying under the NCP and much of the dry zone, as these 'test case' farmers moved

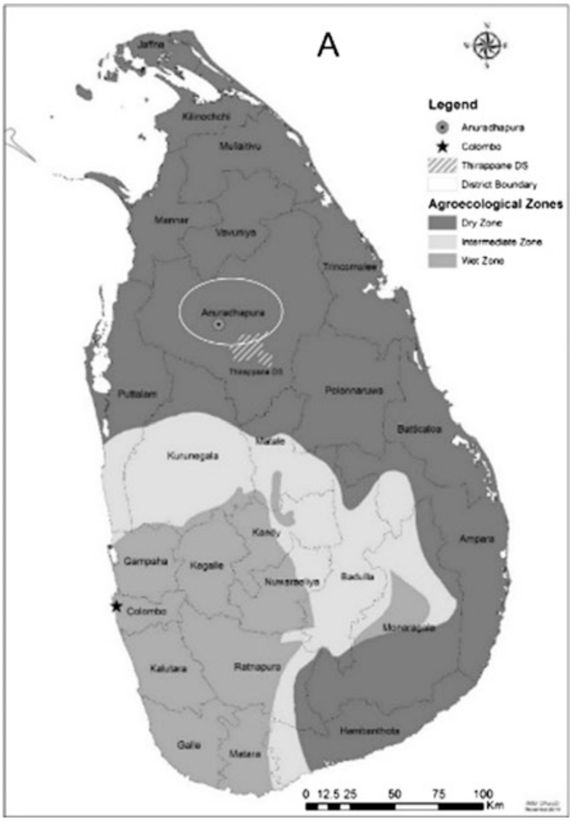


Fig. 44.4 Location of Anuradhapura District

from main subsistence traditional rainfed upland cultivation with low-value crops to cash crops such as soya, chili, and onions (Panabokke 2003) for profit during the dry season.

The success of these test cases saw further investments in this production system with support from donors, NGOs, and provincial ministries, although investments by farmers themselves soon became a major driver in agro-well expansion (Karunaratne and Pathmarajah 2003). Consequently, the number of agro-wells in the dry zone by the year 2000 was estimated to be 50,000, with the highest density in Anuradhapura District (Kikuchi et al. 2003). With this ready source of irrigation, traditional dry season crops such as mustard and finger millet chosen for their drought-tolerant properties have given way to chili and onions today for their profitability. Maize is grown in the wet season giving rise to a mainly two-crop cropping calendar on highland plots. This occurs in parallel to the two paddy crops on lowland plots irrigated by rain and limited quantities of water from small village irrigation tanks. This shift from subsistence to profit-oriented cropping also spurred the expansion of land brought under cultivation. In Puliyankulama village in the Anuradhapura District, for example, this area increased by 470% between the late 1980s to 2012, mainly at the expense of forest land.

Economic Prosperity and Climate-Proofing

This groundwater-driven dry season cultivation system has achieved transformative socioeconomic impacts in the villages where agro-wells have been adopted. The contribution of agro-wells to total household net income per acre (from chili and onions grown in the dry season) is an estimated USD 4,855 or almost 60% of annual agricultural income (Table 44.2), suggesting a more than doubling of households' annual income from agriculture. This is all the more important given that farmers had virtually no earnings from highland cultivation during this season prior to the agro-wells, which translates into significantly higher food security and nutrition during this 'hungry' period. Other dimensions of well-being have also improved as evidenced by increased physical assets such as the high incidence of mechanization (e.g., two-wheel and four-wheel tractors, motorbikes). Not only do the farmers attribute these changes to agro-well production, it can also be inferred from the official employment statistics (Thirappane Divisional Secretary Division 2012) that confirm that only 16% of the population between 18 and 60 years of age

Table 44.2 Net income per acre from lowland paddy and highland cultivation (USD)

Season	Lowland	Highland			Annual net income
	Paddy	Maize	Chili	Big onion	
Wet	1,330	1,699	Not cultivated	Not cultivated	3,029
Dry	237	Not cultivated	2,098	2,757	5,092
Annual net income	1,567	6,554			8,121

Source de Silva et al. (in prep.)

in the study villages that inform this case study are employed outside of farming in public or private employment (de Silva et al. in prep.). In contrast to the virtually full engagement of households in these villages in agriculture, Gamage and Damayanthi (2012) found that in the smallholder agriculture sector overall, as much as 35.2% of farmers who focused mainly on paddy cultivation were 'unemployed.'

Underwriting these changes is the resilience, this agro-well-driven production system appears to provide the face of seasonal water stress, at current levels of extraction. This was demonstrated during the extended dry conditions experienced in the latter half of 2013 and first half of 2014 when net income from chili and onion rose despite two failed monsoons. During this period, farmers without agro-wells or access to surface irrigation abandoned dry season cropping in many parts of the dry zone, resulting in supply shortages in chili in particular. This allowed those farmers irrigating with agro-wells, such as those in these study village, to sell some part of their chili crop at approximately three times the peak farm gate price they would get during normal dry seasons. Another interesting aspect of this resilience lies in the manner in which farmers manage groundwater during times of stress. Despite the absence of any formal institutions for regulating abstraction, de Silva et al. (in prep.) report how individual farmers voluntarily decided to reduce the cropping area by half during the extended dry conditions referred to above, and the seeming prevalence of this behavior throughout their study villages. Representing a seemingly rare example of sustainable groundwater (self-)management, the same authors highlight the observability of the groundwater on a daily basis, and the knowledge of and respect for the resource thereby developed in farmers over time. Central to this approach is also the high economic returns from high-value NPCs, which provides an 'economic space' for farmers to modulate groundwater use in response to different climatic conditions.

Success Has Required an Alignment of Diverse Enabling Conditions

In addition to the access to groundwater, and the resilience such access and the manner in which it has been managed by farmers, this success in alleviating poverty in these communities is derived from a diverse but interrelated set of enabling factors across social, political, institutional, economic, ecological, and physical dimensions. For example, land availability has been critical given the expansion of highland cultivation by conversion of state land (mainly forests). Such large-scale conversion of forests could not have occurred without purposefully lax rule enforcement by line agencies and local government. Interviews by de Silva et al. (in prep.) with law enforcement officers from these agencies confirm that poverty alleviation was consciously prioritized over rule enforcement. The availability of agricultural mechanization has saved on labor and time. The diversification and accessibility of credit sources have facilitated mechanization, following the entry of several private lending institutions and the penetration of service delivery to nearby towns. Similarly, affordable communication technology has linked farmers to diverse service providers including markets, credit suppliers, and state sector service providers.

The concurrent development of agricultural markets has been critical not only in absorbing production, but doing so at prices that have thus far outstripped costs of production and farmers’ perceptions of risk. Government investments in a wholesale market in Dambulla is a major asset, accessed with ease due to improvements in the rural road network, combined with mobile communication that enable farmer-buyer negotiations. Market structure is also central to the current profitability of chili and onions. Their markets are characterized by domestic production deficits to the order of almost 50% of demand (Sri Lanka Government 2008). While the deficit is addressed through imports, changes in domestic output produce sharp price fluctuations through the dry season especially with chili where short-term price spikes grant farmers significant profit margins. This is possible also because of the nature of the specific crop, since chili allows for continuous harvesting once the plant reaches maturity. The sustainability of this production over the past 25 years is also indebted to the three to five small irrigation tanks located in different parts of each village. Meant for irrigating lowland paddy, these tanks nevertheless provide a preexisting groundwater recharge mechanism that underwrites the continued supply of groundwater (Panabokke et al. 2001).

Considering Scalability in the Face of Externalities

By successfully overcoming the historical constraints to profitable cultivation in the dry zone of Sri Lanka, and by demonstrating considerable resilience during normal and exacerbated water stress conditions, the agro-well-based cultivation of high-value OFCs demonstrates significant economic potential for transforming rural dry zone livelihoods. Yet although Panabokke et al. (2001) believe the network of small tanks in the dry zone can support agro-well densities higher than what is recommended, the consensus appears to be that agro-wells are by no means a panacea to the woes of the dry zone farmer (e.g., Pathmarajah 2002; Jayakody 2006; de Silva et al. 2007). Firstly, the fact that the regolith aquifer that underlies much of the dry zone offers limited and spatially irregularly located pockets of water (Panabokke and Perera 2005) has caused concern over over-abstraction, especially when the actual groundwater potential of the aquifer across different parts of the dry zone is not known. De Silva et al. (2007) note that the development of agro-wells has occurred randomly without a general assessment of the hydrogeological properties of the aquifer, the possible yield and a rational siting of wells. The same authors also point out that there is nothing to stop a farmer on private land from exploiting this resource at will, given the absence of regulations specifying well densities.

Concern also exists over groundwater quality (e.g., Kendaragama 2000; Perera 2001), and Jayakody (2006) estimates that around 30% of agro-wells have been abandoned due to such impacts. Senaratne and Wickramasinghe (2011) highlight the impacts of highland cultivation on small tanks by way of accelerated siltation due to farming in upland catchment areas, a process that has been significantly accelerated by the recent spread of commercial highland cultivation. They also refer to instances of chemical runoff causing eutrophication of village tanks, and further suggest the potential for an overall imbalance in local water availability, leading to a decline in the moisture content of the local ecosystem in general.

44.3.1.3 Intensification of Groundwater Use in the Jaffna Peninsula

In the northernmost part of Sri Lanka, lies the Jaffna peninsula, a land trisected by three lagoons (Fig. 44.5). The peninsula, the lagoons, and seven inhabited islands further north of it cover an area of 1,012 km^2, making up the Jaffna District (Jaffna District Secretariat 2015). The peninsula is underlain by a Miocene limestone aquifer, about 100–150 m thick, and consists of an extensive network of karst and channels (Panabokke and Perera 2005). Calcic red-yellow latosols overlie this in most areas, forming soils that are finely textured and well drained with high infiltration characteristics (De Alwis and Panabokke 1972). The highly channeled nature of the aquifer also leads to 50% of annual recharge being lost to the sea (Balendran et al. 1968). While seawater intrusion is an issue at the margins, substantial quantities of freshwater are collected in the center (Kodituwakku 2009). As a result, this Miocene limestone aquifer system is considered to be the richest source of groundwater among the aquifer systems in Sri Lanka, and the most extensively used, historically (Panabokke and Perera 2005).

As none of the 103 perennial rivers that radiate from the central hills of Sri Lanka reach the peninsula, rainfall is the only source of recharge. Eighty percentage of this falls during October and December as the northeastern monsoons and contributes to aquifer recharge. This recharged volume diminishes throughout the remainder of the year (Mikunthan et al. 2013). The dry zone climatic conditions of the area together with high evaporation rates, a short rainfall season and the absence

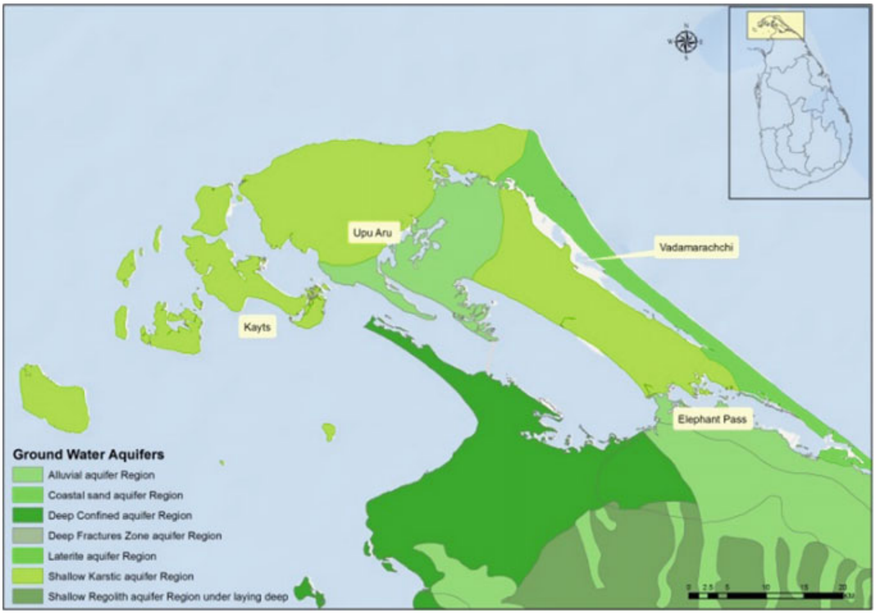


Fig. 44.5 Map of Jaffna District

of fresh surface water bodies of significance, result in groundwater being the only available source of water for human usage.

This dependence on groundwater is framed by Jaffna District being the seventh most densely populated district in the island, with a population of 610,640, in 2013 (Jaffna District Secretariat 2015). Apart from extraction for domestic use, around 80% of the water extracted is used in agriculture that continues to dominate the economy in the district (Panabokke and Perera 2005). Agriculture is the mainstay of economic activity in the area accounting for 44–65% of employment (Jaffna District Secretariat 2015; Thadchayini and Thiruchelvam 2005). Paddy cultivation is mostly rain-fed and occurs at subsistence levels. Incomes come from high-value cash crops, such as red onions, chilies, potatoes, tobacco, vegetables, bananas, and grapes. While these crops are already consumers of large volumes of water, the frequency of cultivation too is extremely intensive. Production is year-round, with no fallowing in between cropping cycles, while pumping can be up to 3 h daily (Mikunthan et al. 2013). An estimated 100,000 dug wells (agro-wells, public wells, and wells for domestic use) operate in the area, of which about 17,000 are agro-wells, with well densities reported to be increasing steadily (Punthakey and Gamage 2006; Jaffna District Secretariat 2015; Sood et al. 2015). Such groundwater development is already considered to be unsustainable, as indicated by Thushyanthy and Silva (2012) who reveal that extraction can be higher than the annual recharge, whereas the safe limit is considered to be 50% of recharge. Apart from the large number of wells and increasing well density, the introduction of electric lift pumps since the 1960s, replacing previous traditional methods, has been a key driver of over-extraction (Sood et al. 2015; Thushyanthy and Silva 2012).

With such intensive use, it is not unexpected that the aquifer already suffers from issues related to salinization and contamination from agriculture and poor urban sewage and solid waste management. As the peninsula is surrounded by the sea, the groundwater exists as a freshwater lens floating above saline water, making it vulnerable to upconing, which results in saltwater intrusion into wells, particularly in areas adjacent to the coast. Sutharsiny et al. (2012) found that 68% of the wells studied in the Chunnakam Aquifer (the largest and most extensively used in the peninsula) had high salinity levels, and 16% had very high salinity. This poses a major threat to the yields of some of the popularly cultivated crops in the area. Nitrate pollution is also prevalent with severe consequences for human health. Mikunthan and De Silva (2008) found nitrate-N levels to be higher than the WHO standards for drinking water in most of the public and farm wells studied. Some studies conclude that up to 80% of wells in the peninsula could be subjected to high levels of nitrate concentrations (Mikunthan et al. 2013). Such contamination in public wells is attributed to the close proximity to soakage pits, the most common form of sewage disposal in households, and in the farm wells attributed to the extensive use of nitrogenous fertilizers. Contamination of the aquifer system also includes point sources of pollution, such as that in Chunnakam, where a power plant is alleged to have leaked 400,000 L of crude oil into the aquifer system (Rink et al. 2016).

Usage of the system can only be expected to expand following the cessation in 2008 of the three-decade-long civil war in the North and East of Sri Lanka. Some of the people displaced have returned to their lands, and many have resumed farming. (Vithanage et al. 2014). The pressure on farming to meet family needs is likely to remain until other opportunities for economic development arise in the area. While any form of further agricultural or industrial development will create further demands on the groundwater system. Concurrent to expanded economic opportunities, the idea of surface water transfers to alleviate pressure on the aquifer has been discussed for many decades. One such scheme is the 'River for Jaffna Project' also known as the 'Arumugam Plan' (named after the engineer who conceptualized the idea) which envisages converting the Elephant Pass Lagoon (see Fig. 44.6) which lies in the east from a brackish to a freshwater body from which water is to be conveyed to the peninsular. This lagoon receives freshwater from a catchment area beneath the peninsula during monsoonal rains, and closing of the mouth of the lagoon is expected to convert it into a freshwater body. Two more lagoons Vadamarachchi Lagoon in the North and the Upparu Lagoon in the West are also to be similarly cut off from the sea, with the water received by the Elephant Pass

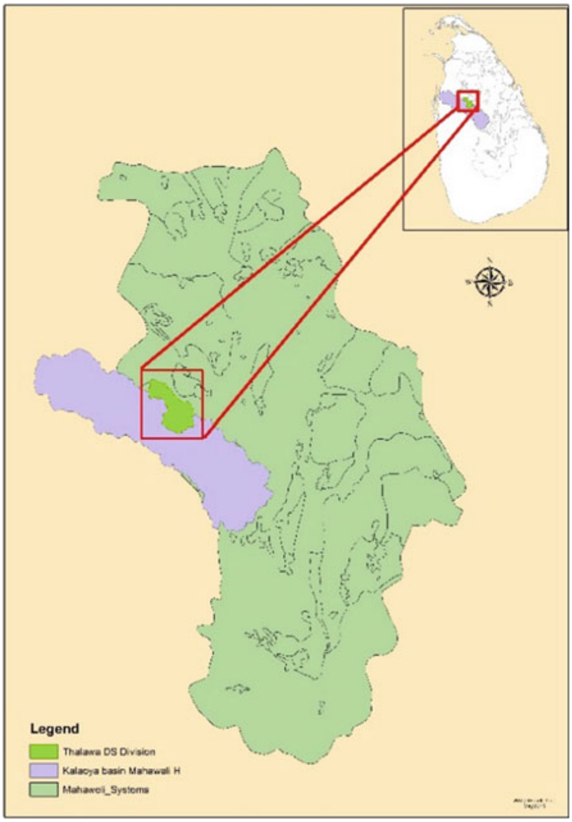


Fig. 44.6 Study area in Mahaweli System H

Lagoon being then transported to these water bodies by a channel. As the Vadamarachchi and Upparu Lagoons account for 10% of the surface area of the peninsula, this concept foresees ambitious results. The benefits expected include improving the quality of water in wells in the peninsula that have become saline as well as facilitating additional pumping without causing saline intrusion and the leaching out salts from the soils adjacent to the lagoons. A cultivation area of 4,400 ha is expected to be supported. (Ministry of Rehabilitation, Resettlement and Refugees 2003; Shanmugarajah 1993). Different components of this scheme have been in implementation at various points in time in the past hundred years, but the infrastructure is now in a state of dilapidation. The increasing urgency of the need to provide the peninsula with good quality water has seen its revival again, by the Irrigation Department, under the Ministry of Irrigation and Water Resources (IWMI 2013a).

This scheme is therefore one that covers the extent of the peninsula, and due to its magnitude, promises to generate benefits that could prove to be a substantial part of the solution. The scale of the problem and the near-complete dependency of the peninsula on groundwater will, not surprisingly, make such a one-stop solution an attractive one to pursue. While in reality, it remains to be seen to what extent these benefits may actually be realized, it is not clear if other implications of changing the ecological conditions of the lagoons have been looked at. Fishing is the second highest source of livelihoods in the district (Jaffna District Secretariat 2015). The ecological services provided by lagoons to fisheries, such as providing a sanctuary to young aquatic organisms is well known, and the Jaffna lagoons are considered to be utilized at substantial levels by the fishermen from the area, for prawn and crab fishing (Sivalingam 2010). The changed salinity levels that this scheme expects to lead to can therefore be expected to impact these fisheries negatively. Thus, the trade-offs that could arise between the expected benefits of such schemes and the impact on the biodiversity of the lagoons and ecosystem services they provide, and the consequent impact on the socioeconomic health of the communities represent important uncertainties to be addressed.

Unlike in the cases of the Kalpitiya Peninsula prior to the 1990s and the North Central Province, and despite well-understood trends such as the salinization of aquifers, instances of collective governance of groundwater use as a common pool resource in the peninsula appear to be missing. In the absence also of any formal groundwater management institutions and paucity of extension services, Arasalingam et al. (2013) find that both irrigation and inorganic fertilizers are used in excessive amounts, with timing of cropping, irrigation, and fertilizer application practices-based mainly on farmers' experience. The uncertainty and lack of permanency created by the war, followed by an absence of suitable formal structures to support farmers no doubt contributes to this.

44.3.2 Conjunctive Use Within Surface Systems

44.3.2.1 Managing Seasonal Water Stress Through Conjunctive Use in Mahaweli System H

While minimizing water losses to seepage in surface irrigation schemes is usually expensive in terms of construction and maintenance costs, such ‘losses’ in fact present opportunities to collect and reuse these ‘losses’ stored as groundwater. Therefore, the prospect of groundwater irrigation is high within surface irrigation command areas due to the recharge of the aquifer from water in irrigation canals, reservoirs, and other distribution systems. These volumes of ‘lost’ water are also substantial given that water use efficiency of the developed water resources in Sri Lanka is very low, largely due to the low level of reuse of groundwater return flows (Amarasinghe 2010). He further pointed out that, conjunctive water use in major irrigation command areas in Sri Lanka is almost non-existent, unlike in other South Asian countries.

The Mahaweli Irrigation Scheme is the largest surface irrigation project ever undertaken in Sri Lanka. The Mahaweli Irrigation Development and Settlement Program are divided into several systems, including A, B, C, D, and H. Rice is the most popular surface irrigated crop cultivated in the scheme as in other surface irrigation schemes in the country. The Mahaweli System H is situated in the Kala-Oya river basin (Fig. 44.6) and covers a total land area of 50,994 hectares, and by 2011, this included 36,119 ha prepared for rice or other lowland crop cultivation. The System H predominantly located in the dry zone has an average annual rainfall 1,018–1,897 mm during the ten year period up to 2003 recorded at the nearest meteorological station Maha Illuppallama that mainly falls during the northeast monsoon, spanning September to February. Water scarcity in the dry season is therefore one of the key challenges for reservoir managers in System H.

The Mahaweli Authority of Sri Lanka (MASL) which manages the Mahaweli system implemented a subsidy program in the 1990s to promote construction of agro-wells (large-diameter dug wells) in System H to minimize water scarcity problems by encouraging use of untapped groundwater resources. However, similar to the previous case studies, rapid expansion of well development has occurred after the year 2000. Although there is often resistance to change from surface irrigation to conjunctive irrigation among line agencies mandated to develop and manage surface water sources, MASL has been an exception. According to the agro-well census conducted by Aheeyar et al. (in prep.) in Mahaweli H during 2014, 4,746 wells have been constructed during the last five years for the purpose of conjunctive use. Groundwater irrigation as a buffer against water scarcity and the unreliability in surface water supplies has clearly become popular in Mahaweli H over the past 15 years. About 70% of farmers using groundwater have invested their own money without subsidies, driven by hopes of minimizing crop failures, increase cropping intensity, and growing high-value crops. Consequently, cultivation of low water consumption and high return NPCs is most popular among 90% of well owners.

The extent under groundwater irrigation ranges from 0.1 ha to over 1 ha. About 55% of the conjunctive irrigation farmers cultivate more than 0.4 ha during the dry season. Over 25% of these farmers own more than one well which indicates the considerable income and the welfare gain from groundwater irrigation to these farmers who have hitherto lived in a traditional surface irrigation scheme. Conjunctive irrigation has therefore positively contributed to the social and economic transition of many households in the area and has allowed previously subsistence farmers to gradually progress to a middle-class status. The average annual household income has increased from LKR 353,000 in surface irrigation to LKR 426,000 and LKR 974,000 in conjunctive irrigation and conjunctive irrigation supported by micro-irrigation technology, respectively. These are increases of 21 and 175%, respectively, compared to surface irrigators. The reallocation of labor time has allowed households to either extend reproductive or leisure activities or alternatively, to use this saved time for productive farm and non-farm economic activities. Enhanced household income has been used to finance to improve the quality of the daily meal, health, and welfare of family members, children's education, improving housing conditions, and improved access to household and farm assets. This economic empowerment and greater control over productive resources have also empowered farmers as decision-making and promoted gender equity. There are changes in inter- and intra-household division of labor with the introduction of non-paddy crops and groundwater irrigation. Assured water supply is made to farmers to perform high input agriculture, which demanded more labor per unit area of cultivation. This has resulted in more opportunities for household and hired labor, especially for women. Enhanced household income allowed farmers to obtain the services of hired labor for agricultural activities that have provided more leisure time for women and children in the farmers' families. Groundwater irrigation also contributes to improve food security and is a viable solution to enhance climate resilience of the farmers. It has therefore been an important means of farmers to improve their livelihood conditions, especially during dry seasons.

The irrigation method adopted by a majority of the groundwater farmers is through surface channels/furrows though this leads to high conveyance losses. Some farmers are in a position to use better agricultural technologies to grow high-value crops that demand less water. Investment made in micro-irrigation (sprinkler) technologies has been spontaneous from their own savings or from credit sources ranging from LKR 10,000 to 240,000 (USD 80–1,890). Farmers are able to repay their creditors the surplus income earned from conjunctive irrigation. The major drivers of the sprinkler technology were water scarcity in dry periods, high labor costs in groundwater irrigation, and labor scarcity.

In spite of this groundwater boom, groundwater levels recuperate to original levels within 8 h after pumping in 95% of the wells during the periods of canal water issues (Fig. 44.7). Only 13% of the wells completely dry up during the driest months of August/September (Aheeyar et al. in prep.). Therefore, there are currently no real water issues reported by the majority of farmers and the depth of wells has not been increased in searching more water or no sign of groundwater depletion. The water scarcity problem in the system is further complicated by serious

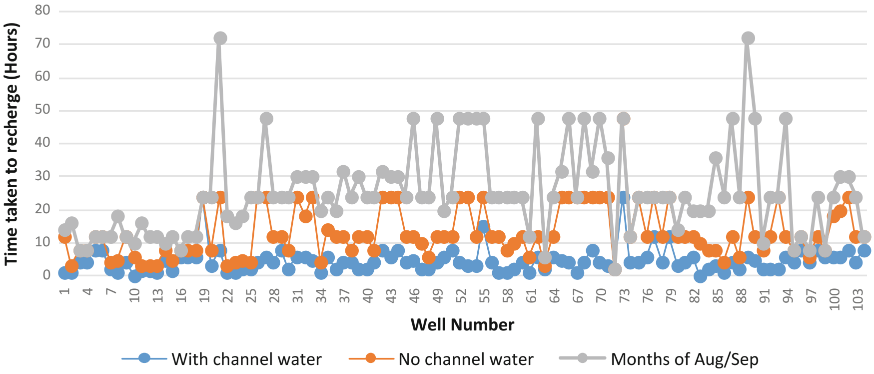


Fig. 44.7 Time taken to recharge well to the original level after pumping. *Source* Aheeyar et al. (in prep.)

groundwater quality issues due to hardness, fluoride, and iron concentration. Only 26% of the groundwater in the basin is completely free from fluoride and 40% of the groundwater is affected by unsafe iron concentration (Bandara n.d.; quoted from Saleth et al. 2007).

According to observations made by Water Resources Board, whenever water flow takes place in the canal network (main canals, branch canals, distributary canals and field canals) of Mahaweli System H, the regolith aquifer within the irrigation scheme get fully charged with the seepage and infiltration water from canals to a specific height according to the lay of the landscape. This water table recedes at a slow rate after irrigation supply through the canals is cut off (Panabokke and Perera 2005). Therefore, there is a limit in the utilization of shallow water table and any over-extraction of water during cessation of water in the canals in the absence of any governance arrangements would lead to negative externalities in the system.

The existing water sector agencies often tend to focus and limit their scope to historical water supply development mandates and find it difficult to grasp or incorporate conjunctive use opportunities. The promotion and implementation of improved conjunctive use and management of groundwater and surface water resources required significant strengthening of the existing institutional arrangements for water resource management, proper coordination among the water management agencies, and gradual institutional reform from the lessons of the experiences of pilot projects. An awareness creation effort from the government water sector agencies would facilitate the social learning and institutional development process and lead to the promotion of attitude changes and the acceptance of implementable regulations.

The performance of conjunctive irrigation farmers indicates that major irrigation schemes like Mahaweli H have aquifer space for storage of recharge water, and stored water is economically accessible at the needed time. Irrigation reservoirs and channel networks are playing a great role in the replenishment of groundwater aquifer through seepage and percolation losses. The stored groundwater can be effectively used to fill the gap in water availability through proper planning of the conjunctive use of available surface and groundwater. Underutilization of groundwater is a potential problem, especially in surface irrigation command areas, where alternative water supply options are considered at greater environmental and economic costs. Therefore, the lost opportunity of implementing conjunctive irrigation needs to be on the agenda of line agencies to improve the livelihoods of poor farmers.

44.4 Discussion: The Governance Challenge of Balancing the Benefits and Risks

44.4.1 Emerging Values of Groundwater Use and Attendant Risks

The case studies presented in Sect. 44.3, together with the existing literature demonstrate clearly the significant positive impacts that emerging models of groundwater development are having on rural poverty alleviation and food security. Of particular significance is that these gains accrue during the dry season—the period when traditionally households face the greatest food security and livelihoods constraints. At the heart of this agrarian livelihoods revolution, be it still in limited geographical areas, are the humble pump and associated technology that have almost silently (Shah 2013) freed smallholder farmers from the collective decision-making processes that characterize surface water irrigation schemes controlled by state rules. Pumps, by shifting control over the water itself and irrigation decisions to individual farmers, have injected a new energy into farmer entrepreneurship, seen not just in their diversification to high-value non-paddy crops, but in their innovation in adapting technology to suit specific production needs and biophysical conditions, as noted in Kalpitiya, and willingness to risk private funds without waiting for the next government handout that characterizes all three case studies. This access to groundwater along with control over how it is used has, subject to concerns discussed below, generated a new resilience to seasonal and climatic water stress. One notable difference between this groundwater economy in Sri Lanka and others in South Asia as noted by Shah (2013) is that groundwater mainly irrigates high-value crops in Sri Lanka, while in other countries it is used primarily for paddy, which makes little economic sense. Groundwater irrigated farming in Sri Lanka generates 4–5 times the income compared to other South Asian countries[4] A preoccupation with paddy has also driven down groundwater levels as is the case in northern Bangladesh (Qureshi et al. 2014), India, and others.

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[4] The authors recognize that although these benefits are distributed equally among groundwater users, what is relevant for this discussion is the overall upliftment of households' livelihoods.

Contrasting with these important socioeconomic benefits are growing concerns in Sri Lanka over the sustainability of groundwater resources from both quantity and quality standpoints. With respect to the former, over-extraction issues are problematic primarily in the shallow unconfined karstic aquifers, lateritic (cabook) aquifers, and shallow regolith aquifers. Many observers such as Panabokke (2003) have cautioned about the rapid and haphazard development of wells taking place without understanding the nature and behavior of the aquifers. Shah (2013) in fact notes that India began developing low-yielding hard-rock aquifers suitable for intensive groundwater use in the 1970s, and that Sri Lanka is following suit where the relatively thin groundwater layer means this shallow aquifer is limited in its quantity (Senaratne 1996), causing Dharmasena (2001) to recommend that only 25% of its potential groundwater storage be exploited. However, while recognizing these limitations, Panabokke and Perera (2005) believe that this aquifer nevertheless represents a highly renewable groundwater resource due to the abundance of the small irrigation tanks through much of the dry zone providing unmanaged aquifer recharge. A different challenge arises by the fact that in the regolith aquifer there is no continuous body of groundwater with a single water table in the crystalline rocks, but rather separate pockets of groundwater each with a distinct water table (Cooray 1988). This makes clear the importance of ensuring sufficient knowledge exists to ensure effective well location. According to Panabokke and Perera (2005), the coastal sand aquifer is also under stress due to human and agricultural activities. Similarly, Thushyanthy and Silva (2012) reported that the groundwater withdrawal from the shallow limestone (Karstic) aquifer in the Jaffna peninsula is 16% higher than the average annual recharge of the aquifer.

Concern over groundwater quality arises from natural conditions as well as a range of dispersed human activities (Table 44.3) including over-extraction, sand mining, poor waste and wastewater management, and high rates of especially nitrate containing agrochemicals (Wijesekara 2013). The increased cropping intensities and reliance on agrochemicals that characterize groundwater-based agriculture is therefore seen as a major externality. These not only introduce pollutants, but also cause land subsidence and seawater intrusion through excessive groundwater extraction. Poor management of domestic and industrial waste is another significant consideration, with growing impacts on groundwater quality either directly or through surface water and soil pollution. Increasing solid waste generation on the one hand, and vastly insufficient sanitary landfills or incineration options on the other hand, increases the impacts of leaching from both domestic and industrial sources. Industrial zones generate significant volumes of hazardous waste, of which as much as 75% do not reach a sanitary waste site. Consequently, the contribution to groundwater pollution from poor waste management is now considered as important as agricultural sources at least within the Central Environmental Agency (CEA officials, pers. com.).

Table 44.3 An overview of groundwater contamination and their drivers

Region	Province	Aquifer	Contamination	Causes
Jaffna	Northern	Shallow karstic	Enhanced levels of nitrate pollution with high levels of chloride and salinity	Overuse of agrochemicals. High settlement density with poor sewage effluent disposal from pit latrines. Excessive groundwater use, seawater intrusion
Kalpitiya Peninsular	Northwest	Coastal sand	Nitrates, chlorides and potassium, four times the WHO guideline values; seawater intrusion	Intensive cultivation, excessive fertilizer use, and untreated wastewater
Puttalam	Northwest	Coastal sand	Very high levels of manganese and salt. High levels of total dissolved solids in some locations	Over-extraction. Seawater intrusion. Organic pollution through liberal use of organic manure and inorganic fertilizer. Shrimp aquaculture
Chilaw	Northwest	Coastal sand	High concentration of iron and salt	
Northeastern region	Northeast	Coastal sand	Seawater intrusion	Over-abstraction
Anuradhapura, Polonnaruwa	North central	Regolith	Fluoride	Geogenic formation
Colombo and Gamapha Districts	Western	Lateritic	Geogenic contamination related to iron and acidity in the lateritic formation	High extraction for industrial estates, tourism industry, urban housing and bottled water, Industrial pollution

Source Authors' compilation from multiple sources

44.4.2 Heading Toward Anarchy? The Current 'Governance Deficit' in Managing Groundwater and Ways Forward

The trajectory of groundwater development in Sri Lanka, as described in this chapter, aligns with Shah's (2009) portrayal of groundwater governance in South Asia as an anarchy of atomistic pump irrigation, where control over water resources has shifted from the state to individual farmers in the case of groundwater. If not already anarchistic in nature, the groundwater development scenarios that occur with very limited, if any, management oversight suggests groundwater use in Sri

Lanka is at least on the same trajectory as India and other South Asian neighbors. With high returns on investments for farmers further random expansion of abstraction appear very likely. As such, a key defining characteristic is this 'governance deficit' or the gap between rapid developments on the ground driven predominantly by private investment, and inaction in balancing resulting benefits and negative externalities on the part of government, arguably still preoccupied with surface water delivery.

The following discussion around this governance deficit brings to the fore the paralyzing effect of institutional compartmentalization with respect to water resources management that contrasts not only with the classic common pool resource nature of groundwater (Villholth and Giordano 2007), but also of the connectivity between ground and surface water for optimizing water resources overall. Villholth and Rajasooriyar (2010) point out that planning for effective and sustainable groundwater use requires considering surface water systems and describes surface water as a reflection of groundwater. This approach is currently mostly absent in Sri Lanka where groundwater and surface water are still thought of as two separate resources. This is despite the dense network of rivers, many of which are fed by groundwater (Vilholth 2013).

One cause for this dissonance in the manner in which surface and groundwater are conceptualized is a national consciousness honed to think of water in terms of surface flows over at least two millennia. Not only did the past kings of Sri Lanka focus almost exclusively on surface flows, the vast majority of water sector investments by post-colonial governments have followed suit, except in the case of domestic water supply. As aptly noted by Samad (2013), 'we do not see politicians inaugurating a tube well or a public well… we do not see bureaucrats around that.' This emphasis on surface flows is also reflected in the structural composition of water-relevant institutions (Table 44.4), all of which, with the exceptions of the

Table 44.4 Key organisations relevant to groundwater management

Organization	Overall mandate	Links to groundwater
Water Resources Board (WRB)	An advisory body to the Minister on all matters concerning the control and use of water resources in Sri Lanka with emphasis on groundwater	Assumed the primary mandate for groundwater management since 1999. Identification, investigation, and development of groundwater resources in the country. Maintains a database of hydrogeological and other information related to groundwater and its use
National Water Supply and Drainage Board (NWS&DB)	Responsible for the domestic and industrial water supply and sanitation	Installation of groundwater-based public and private water supply schemes for domestic and industrial purposes. Collects geological and spatial data on bores, agro-wells and water supply wells which they construct.

(continued)

Table 44.4 (continued)

Organization	Overall mandate	Links to groundwater
		Maintains a database of hydrogeological information to inform its groundwater use—includes considering cumulative impacts
Irrigation Department (ID)	Development of land and water resources for irrigated agriculture. Preparation of Master plans for development of the different river basins for the optimum utilization of land and water resources. Integrated Water Resources Management and Participatory Management in Major/Medium Irrigation systems. Project formulation and detail designs of Irrigation, Hydropower, Flood control and Reclamation Projects	The activities and the performance of the department on their mandated activities of operation and maintenance of major irrigation schemes, drainage and flood protection schemes and salt water exclusion schemes, which has an impact on quantity and quality of available groundwater resources in the irrigated command areas and beyond
Department of Agrarian Development	The Department is responsible for the management of village irrigation (Minor irrigation) schemes and also mandated to implement Agrarian Development Act (2000)	Minor irrigation cascade recharged the groundwater aquifer in the dry zone where agro-well cultivation is more popular. Agrarian Development Act has provisions to regulate the digging of agro-wells, though it is not enforced
Mahaweli Authority of Sri Lanka (MASL)	Overall mandate over water management and cultivation programmes in the declared Mahaweli Project regions, as well as other basins which have been declared by the government as special areas	MASL's Water Management Secretariat co-ordinates with other operating agencies, creating scope for brining groundwater into agricultural strategies
Extension and Training Division (Department of Agriculture)	Enhancing access to hard and soft technologies for land and water management at farm level and farmer capacities to engage in value chains	Dissemination of new technologies related to the water management including micro-irrigation
Central Environmental Authority (CEA)	Regulates industrial pollution by establishing standards and licensing linked to Initial Environmental Examination (IEE) and Environmental Impact Assessments (EIA). CEA is a national level regulating institution to prevent and control pollution of water resources	IEEs and EIAs required to consider impacts on groundwater contamination. It deals with on-site pollution of groundwater mainly through the issuing of Environmental Pollution Licenses (EPL) that can either be withheld (i.e., not issued) or include conditions for groundwater management (e.g., requiring on-site waste management)

(continued)

Table 44.4 (continued)

Organization	Overall mandate	Links to groundwater
Geological Survey and Mines Bureau	Responsible for geological mapping and implements the Mines and Minerals Law No 4 of 1973 which is mandated to prospect for minerals and explore and appraise the island's mineral resources	Survey activities provide important knowledge on geology-groundwater relationships. However, mining activities including surface sand mining threaten aquifers as well as recharge capacities
Municipal Councils, Urban Councils, Pradeshiya Sabhas, and Divisional Secretariats	Empowered to provide local water supply services for the benefit of persons residing within their areas of jurisdiction and management of solid wastes generated in the respective divisions	Delegated authority from the CEA for issue of licenses to and monitoring some industry types Also provide local water supply and sanitation, small-scale and provincial irrigation and drainage activities
Provincial Councils	Overall developmental planning and plan implementation in each province	Several water-related functions were handed over to the Provincial Council through the implementation of the 13th Amendment to the Constitution of 1987
Board of Investment of Sri Lanka	A central facilitation point for investors, mandated to expand and strengthen the base of the economy. Focuses on encouraging Foreign Direct Investment. Establishes Investment Promotion Zones throughout the country. BOI companies account for nearly 65% of all exports and 86% of industrial exports	Significant direct use of groundwater as well as direct and indirect impacts on groundwater quality through water and soil pollution. Issues Environmental Protection Licenses for BoI approved industries, but needs CEA's concurrence along with any conditions the CEA may impose
Registrar of Pesticides (ROP) (Under the Department of Agriculture)	ROP regulate the importation, storing, and selling of agrochemicals including pesticide formulation, packing, labeling and monitoring pesticides exposures occur during formulation, storage, and use. Enforcement based on registration of pesticides, but does not directly regulate or monitor pesticide at user levels	The post-registration monitoring activities of pesticides are dormant and carried out on an ad hoc basis due to lack of trained manpower, insufficient financial allocation, lack of laboratory facilities or non-availability of laboratory facilities and other field support requirements which could lead to misuse, overuse, and abuse of pesticides causing water and environmental pollution

Source Authors' compilation

Water Resources Board (WRB) and the National Water Supply and Drainage Board (NWS&DB), predominantly utilize surface water, although many enjoy the option of exploiting groundwater. Groundwater has therefore been quite literally ‘out of sight, out of mind.’

In fact, it was not until 1999 that groundwater received a focal agency in the form of the Water Resources Board, following amendment of the Water Resources Board Act No. 29 of 1964 in that year. Originally established as an advisory body to the minister on all matters concerning the control and utilization of water resources in Sri Lanka, the WRB’s focus became groundwater. It consequently conducts policy-oriented research on groundwater and maintains a database of hydrogeological and other information related to groundwater and its use. However, the fact that the WRB recognizes the need to work with at least 18 authorities/organizations either in respect of groundwater or surface water[5] is an illustration of the challenge faced in coordinating a holistic governance response to the rapidly evolving groundwater development on the ground. These agencies represent not only those with some role in groundwater management, but also sectors that may directly or indirectly impact this resource. A number of these agencies are highlighted in Table 44.4 which also serves to emphasize the compartmentalization of water resources management at national planning scale, but nevertheless, the opportunities available for collaboration in developing a coherent and rational groundwater strategy. Such coordination will also have to address the absence of an effective institutional mechanism that promotes conjunctive use of surface and groundwater.

This absence of a coordinating influence has blunted the mandate over groundwater bestowed on the WRB and maintains a status of segmentation and duplication. For example, the National Water Supply and Drainage Board (NWS&DB) also conducts research on groundwater and also maintains a database for the purpose of supporting its mandate of providing drinking water, even though groundwater extraction for this purpose and for agriculture and other needs occur from the same aquifers. Consequently, no single database provides a complete picture of wells constructed in the country. The issue of basic data for the framing of a more coherent approach to groundwater governance illustrates this issue well. The existence of knowledge gaps and the unavailability of 30 years of research results (Panabokke and Perera 2005) for planning purposes has been consistently highlighted as a fundamental constraint (e.g., Ferdinando and Premathilake 2013; Villholth and Rajasooriyar 2010). Much of the existing data is also geographically limited, and some may be outdated given the rapid increase in recent groundwater use (Karunaratne 2013). The piecemeal nature of research and monitoring, and the residence of results in various state, private and non-governmental organizations mirrors the current institutional failure to coordinate a resource governance response.

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[5] Water Resources Board http://www.wrb.gov.lk/web/.

This failure is also visible in the absence of a policy, guiding principles and rules on for sustainable and socially equitable groundwater management. The subject of groundwater has been a victim of the failure over nearly two decades to formulate a comprehensive national water policy, with past attempts falling foul of strong political interests linked to poor public awareness of the issues. An important aspect of future attempts at policy as well as rule formulation is to ensure flexibility to reflect the differing hydrogeological and groundwater use contexts across the different aquifers—a challenge impossible without sufficient data that is collected and made available systematically. Specific data and regulatory issues identified based on several sources (e.g., Ferdinando and Premathilake 2013; Villholth and Rajasooriyar 2010; Panabokke and Perera 2005) include:

- Concerns over consistent data standards, accuracy and reliability of data and information both between databases and within the same database;
- Insufficient knowledge of groundwater dynamics at operation level (e.g., recharge mechanisms, recharge levels, flows, and transport) as well as the spatial variation of water quantity to address over-extraction causing quality changes and finally well failure.
- Understand the socioeconomic implications of groundwater use and threats.
- Identifying sensitive and vulnerable areas of groundwater pollution due to natural and anthropogenic reasons, including chemical processes in the aquifer systems;
- Effects of climate change on groundwater;
- Integrated region specific groundwater models leading to groundwater vulnerability maps;
- The need for coordinated construction of wells in the same aquifer by different agencies, and sometimes even the same agency;
- Addressing the lowering of the general groundwater table (aquifer drainage) due to sand mining along rivers, and decreasing recharge related to aquifer drainage, and
- Opportunities for artificial recharge.

Of particular note is the need for a system that can generate, organize and convey a continuous stream of real-time data for groundwater management to ensure different stakeholders are aware of conditions and can use the data in planning (IWMI 2013b). This status quo contrasts unfavorably with surface water where understanding already exists to develop and utilize most if not all surface water resources (IWMI 2013b).

In the absence of a coordinated information and awareness system, despite a considerable amount of essential and basic data, Panabokke and Perera (2005) point out quite fundamentally, that Sri Lanka's groundwater resources are seriously misunderstood by decision makers and also by major groundwater users. Given the range of sectors across which data is needed, Panabokke and Perera (2005) also highlight the critical need for a coordination mechanism to ensure any concerted research program is well coordinated, thereby addressing a major gap in the governance framework. It could be further argued that bridging this gap to provide a more coherent picture of the resource base, its use and impacts should in fact represent the beginning of a coordinated process that leads from greater understanding to effective management. As such, improving understanding of the resource, its use and challenges should provide a strong impetus and a point of focus for greater institutional collaboration in filling other gaps in this broader governance landscape.

Attempts at institutional building to address these fundamental issues shaping the current governance of groundwater resources are likely to also contend with issues around capacity, both human and financial. In addition to the manpower and other resources needed for a more comprehensive research and monitoring program, Table 44.3 makes clear that a good number of drivers, especially of groundwater quality, depends on the capabilities and commitment of other sectors. This is well illustrated by the lack of proper wastewater and solid waste management facilities and systems in urban and industrial centers. While agencies such as the Central Environmental Authority now recognize the hitherto under-appreciated threats to groundwater quality posed by waste (CEA officials, pers. com.), the paucity of enabling rules, processes and physical infrastructure for effective waste management represents a major part of this groundwater governance deficit. The absence of sufficient waste disposal capacity such as sanitary landfills and incinerators is a fundamental roadblock and results in growing urban garbage dumps. The garbage dumping site at Meethotamulla on the periphery of Colombo, for instance, has existed for over 20 years, with unknown levels of leaching of pollutants into the soil and local waterways.

The absence of centralized waste management facilities has also placed greater emphasis on-site-based action which however is marked by illegal on-site waste disposal practices that are difficult to trace, and poor rule enforcement. Even where such illegal practices are known, the offending industrial operators are rarely prosecuted due to fear of undermining employment opportunities. In addition to the links this highlights to broader developmental considerations, it also implies that illegal disposal is widespread within industry. A related weakness is the exemption from EPLs enjoyed by industrial operations that employ less than 200 people. These are treated as domestic enterprises despite their significant cumulative capacity to pollute. The EPL regulatory system is further weakened by the fact that for those industrial operations that do require an EPL, this comes into play only after the building and other structures are constructed, often leaving no physical space for a treatment facility on-site. Even where room is available, retrofitting such a facility may be costlier than if it had been integrated in the structural designs from the outset.

The devolution of the granting of EPLs to the Provincial Councils established through the 13th Amendment to the Constitution of Sri Lanka is yet another source of weakness in two ways. The first relates to low staff capacity, whereby putting the pollution in the ground is seen as a solution and not a problem. Such issues are being addressed by the CEA through training. The second issue arises from the Provinces' ability to deviate from rules set by central government, as is currently the case with respect to the Northwestern Province where it Environmental Act does not require the BoI to seek formal approval from the Environmental Authority of that province. While this is currently being remedied by the CEA, it does highlight the additional institutional and political complexities created by the devolution of regulatory powers. It may however be argued that this devolution offers be it untapped opportunities for more localized and context-oriented management regimes to evolve, given the diversity of aquifer types and other ecological and social contexts.

Compounding these practical gaps around groundwater pollution is the absence of an agency that is assessing the risks to groundwater posed by different industries. Although the CEA analyses treated effluents using upstream and downstream samples in rivers, it does not currently consider impacts on groundwater. Similarly, while addressing soil pollution is included as a function of the CEA in National Environmental Act that governs the CEA's mandate and functions, it has not featured in this agency's focal areas around pollution management. This is in addition to poor waste management capacities of provincial and local government authorities.

44.4.3 The Nascent Groundwater Monitoring Network: A First Step Toward Closing the 'Governance Deficit'

Given the central role played by information systems, the WRB's current attempt to establish a groundwater monitoring network represents a potentially major step in addressing the hitherto fundamental issue of data. When complete, this network will consist of 1,300 data loggers covering the entire island including 103 river basins. A real-time groundwater database will support a coherent groundwater management system by supplying data for decision makers, researchers, stakeholders, and the general public. This network will in fact be central to the future plans of WRB regarding management of groundwater (Karunaratne 2013) which include groundwater modeling under various scenarios; hydrogeochemical modeling; optimization modeling; preparation of groundwater vulnerability maps and community participation and awareness programs to actively enroll civil society in minimizing pollution and over-abstraction in the first place. The rationale appears to view such an investment as a lever to generate change in institutional behavior necessary to translate adequate data into effective management responses.

The first phase of this network established over 2014 and 2015 consists of seven pilot Divisional Secretary Divisions (DSDs), selected to focus on a specific management challenge. These include extensive agriculture including areas using agro-wells; areas with a high incidence of kidney disease, and areas with industrial pollution, salinity, and other qualitative issues. The activities in each DSD include geophysical surveys, test bore hole construction, pumping tests, water quality analysis (physical, chemical, heavy metal, bacteriological, and pesticides) and DGPS leveling of monitoring points. While this pilot phase has been made possible under the donor funded Dam Safety and Water Resources Planning Project (DSWRPP), this also instills uncertainty regarding continuity post-project. The current expectation is that expansion of the network to the entire country and its sustenance will be financed by the government, or through further donor funds (IWMI 2013b). If used effectively, a strong case for government support exists by way of potentially significant government savings by avoiding expensive remedial interventions as well as production losses and adverse impacts on human health.

44.5 Conclusions

The case studies presented in this chapter represent different models of growing groundwater use in the agriculture sector, across different regions of Sri Lanka. The case on the Jaffna peninsula shows how context driven traditional dependence on groundwater is intensifying. The other three examples are of relatively recent production systems driven by an increased affordability and availability of technology for tapping groundwater, and the desire by households as well as government to overcome seasonal surface water scarcity as well as climatic uncertainty. That groundwater is rising to prominence even in part of the Mahaweli surface irrigation scheme also suggests the confluence of other anthropocentric drivers such as population pressure and increased water demand from other sectors of human activity. That all applications of groundwater are linked to diversification high-value commercial crops with low water demands relative to paddy is a key element in the transformative economic benefits from groundwater exploitation to previously mostly poor rural households. Indeed, this groundwater high-value crop combination sets Sri Lanka's groundwater use apart from its neighbors in South Asia. Large economic benefits have over time also helped farmers take control of investments in groundwater which, while an important attribute at farmer scale, threatens to continue the haphazard nature that has characterized groundwater use expansion to date. This is especially of concern with respect to the regolith aquifer that underlies the majority of the country, but offers limited groundwater potential. Other aquifers such as the sandy coastal aquifers and that in the Jaffna peninsula offer higher potential, but offer different causes for concern such as the higher irrigation frequency demanded by sandy soils, accelerating aquifer contamination. Concerns over contamination, arise in each example of groundwater use, and thus emerges as a major area of concern, especially in light of the considerable costs of remedial action. That this contamination is linked to drivers other than agriculture also highlights the dispersed components to be addressed in managing this issue.

The benefits from groundwater use are thus clearly significant, as is the vulnerability of aquifers from qualitative and quantitative standpoints that threaten the foundations of these production systems. Balancing these trade-offs and providing a rationalizing influence in these production systems thus emerges as the critical policy and regulatory challenge. The current institutional architecture however is drawn along hard lines of delineation between various service delivery functions (irrigation, domestic supply) and water sources (surface and ground) will need to acquire a conceptual and structural flexibility to adapt to ground realities where these distinctions are already fading. The current institutions in fact reflect a hydrosocial history dominated by surface water resources. However, three developments suggest movement toward meeting the groundwater governance challenge. The first is the recognition of the fundamental need for a more systematic process for generating and sharing information on groundwater resources, their interactions with human society and resulting feedback loops. The second is the emergent attempts to address this knowledge gap in the form of the recently initiated groundwater monitoring network. The third source of optimism emerges from the field level where key agencies such as the MASL as well as the Irrigation Department are already working with farmers to adapt to growing water scarcity and uncertainty (in Mahaweli System H) by combining surface and groundwater flows. It is hoped that such cases can provide the knowledge and attitudinal shifts necessary for such adaptive management at larger scales.

These developments are however only a beginning and subject to uncertainty. The groundwater monitoring initiative, for instance, is financed by time-bound donor funding, and thus its continuation will depend on government commitment or further donor support or a combination of the two. Moreover, while individual agencies demonstrate the imagination for adapting conventional approaches to irrigation, this may not wholly compensate for the absence of an institutional mechanism to ensure overall water resources planning and policy setting spanning all water demands in light of all management options. An important and interesting dimension to this challenge is the heterogeneity in groundwater resource availability given the six aquifer types in the country, linked to varying types and degrees of use, from the traditional groundwater culture on the Jaffna Peninsula, to the emerging groundwater markets. While a systematic data system will contribute to making these geographically specific challenges more explicit, it is suggested that the delegation of powers to provinces through the 13th Amendment to the country's Constitution will be an important factor in resolving the question of what scale might be most appropriate for groundwater management. Here too, the spatial misalignment between aquifer and administrative boundaries may add another layer of complexity.

Annex: Different Types of Aquifers and Their Occurrences in Sri Lanka

	Aquifer type	Occurrence and distribution	Salient features
1.	Shallow unconfined karstic aquifers	Occurs in the channels and cavities of the Miocene limestone formation. Distinctly bedded, well joined and highly karstified. The whole of Jaffna peninsula is underlain by this formation. All the shallow water originates from rainfall infiltration	Generally, 100–150 m in thick with an average of 60 m. Karstification intensifies the subsurface water flow and causing significant water loss (around 50%), especially along the coastal lagoon. Around 80% of the remaining water is used for agriculture and rest for domestic use. The estimated usable groundwater is 10–25 million m^3
2.	Deep confined sandstone and Miocene limestone aquifers	Occur within sedimentary limestone and sandstone formations of the northwestern and northern coastal plains. Sedimentary limestone is highly faulted and separates the aquifer into a number of isolated blocks. Seven distinct groundwater basins have been identified and named as Mullaitivu, Vanathavillu, Kondachchi, Murunkan, Mulankavil, and Paranthan	These are relatively more than 60 m in deep and one of the richest groundwater basins in the country with Artesian conditions. These aquifers expand during rainy season and contracts in the dry season. About 125,000 ha of high-value intensive agriculture, intensive human settlement, and flourishing coastal tourism industry are supported by these aquifers
3.	Coastal sand aquifers	Consist of three different types, i.e., Shallow aquifers on coastal spits and bars (type 1) found in Kalpitiya, Pooneryn, and Mannar island in the northwestern region; Shallow aquifers on raised beaches (type 2) found in Nilaweli-Kuchchaweli, Kalkuda and Pulmoddai in northeastern region and moderately deep aquifers on old red and yellow sands of prior beach plains (type 3) found in Katunayake and Chilaw	These aquifers expand during rainy season and contracts in the dry season. Total extent under type 1 and type 2 aquifers is estimated to be 140,000 ha that supports high-value intensive agriculture, intensive human settlement and flourishing coastal tourism industry are supported. Extent of type 3 aquifer is around 40,000 ha
4.	Alluvial aquifers of variable depth	Occur in coastal and inland floodplains, inland river valleys small rivulets, and old buried riverbeds	Alluvial formation in the larger rivers varies from 10 to 15 m and up to 35 m in thickness and may extend to several hundreds of meters on either side of river beds.

(continued)

(continued)

	Aquifer type	Occurrence and distribution	Salient features
			Groundwater potential is very high in these aquifers and water could be tapped continuously for industrial and agricultural purposes
5.	Lateritic (cabook) aquifers	Occurs in the southwestern low-lying parts of the country. Aquifer is highly fragmented into a number of discreet, low mounds	It has considerable water-holding capacity depending on the depth of the 'Cabook' formation. The storage capacity of the complex mosaic of meso-aquifers is large due to the high porosity of the typical cellular honeycomb structure. Easily accessible to shallow dug wells and tube wells. The water table can recede up to 15 m below the ground during the dry periods for more than 65 days. The aquifer recharge rate is fast due to its structural characteristics and location in the wet zone
6.	Shallow regolith aquifers of the hard-rock region	Groundwater in these formations is found as separate pockets formed in the shallow weathered mantel rock (regolith) or in deeper fracture zones of the unweathered material. Occurs in the north central and northwestern part of the island	Aquifer in the weathered zone generally ranges from 2 to 10 m in thickness, while the fractured zone is located at more than 30–40 m depth. Limited groundwater potential due to low storage capacity and transmissivity of underlying Crystalline basement rock. Nearly nine-tenths of the country is underlain by crystalline hard rock. Agro-wells have been mainly constructed in these aquifers

Source Adopted from Villholth and Rajasooriyar (2010), Panabokke and Perera (2005), Panabokke and Sakthivadivel (2002), Panabokke (2007)

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