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Natural and human-induced drivers of groundwater depletion in Wadi Zabid, Tihama coastal plain, Yemen

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Groundwater depletion is a problem in many parts the world. We developed an approach to investigate the drivers of groundwater depletion in data-scarce regions. The approach combines natural and human-induced drivers, with the latter focusing on the link between human activities and government policies. We tested the approach in Wadi Zabid, Yemen. Forty years of rainfall-runoff data were analyzed, alongside changes in land cover, groundwater abstraction and related policies. No decrease in rainfall was observed, but runoff did decrease slightly. Significant expansion of agricultural lands led to increased demand for irrigation water, which was provided by drilling wells and building water harvesting/diversion structures. In Wadi Zabid, human activities, stimulated by policy measures, were the main drivers of groundwater depletion (water table here fell by 1 m/yr on average over 1972–2016). We conclude that combining natural and human-induced factors is indeed a valuable approach for investigating groundwater depletion drivers.

Keywords: groundwater depletion; Wadi Zabid; water and agriculture policies; rainfall-runoff; human factors driving groundwater depletion

1. Introduction

Human activities, in combination with natural phenomena, significantly impact the availability and quality of groundwater resources. However, drivers of groundwater depletion have often been studied from either a natural or a human-induced perspective. Few studies have focused on both types of drivers and included links between human activities and government policy measures. The result has been partial explanations of the causes of depletion. Indeed, both land use/land cover and climate change have major impacts on catchment hydrology and largely determine the rate of replenishment and depletion of groundwater systems (Calder 1993; Li *et al*. 2009; Taylor *et al*. 2013; Gain and Wada 2014). According to Grum *et al*. (2017), agriculture and the building of water harvesting and diversion structures are the main drivers of changes in land cover[1] and associated hydrological processes. Rainfall scarcity and

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reductions in runoff have diminished groundwater recharge in many places, with the effect often most severe downstream. Also, in arid and semi-arid zones, most aquifers show significant depletion because water withdrawal rates are greater than natural rates of recharge (Famiglietti 2014). For coastal aquifers, the problem is more complicated where seawater intrusion has become a worldwide environmental problem due to groundwater overexploitation (Cai, Taute, and Schneider 2015; Colombani, Mastrocicco, and Giambastiani 2015; Javadi *et al*. 2015).

Human drivers play a fundamental role in stimulating or limiting water consumption (Graham *et al*. 2020). A region's water consumption can be particularly affected by agricultural production, associated for example with population and economic growth, changes in crop patterns and irrigation practices. The other human drivers that influence agriculture and thus water consumption are governmental decisions and policies. Through these, governments choose to incentivize certain paths of economic growth and development, for example, stimulating agriculture with the construction of dams, weirs and canals to enable expanded use of irrigation. Other policies that influence agriculture are subsidies or taxation on agricultural inputs, bans on agricultural imports or exports, loan availability and agricultural marketing also influence the extent to which agricultural activities expand or contract. On the contrary, decisions strengthening infrastructure regarding construction and development of wastewater treatment plants and desalination plants can reduce the increasing depletion of groundwater. In addition, regulation by government via decisions and legislation would control water use and agricultural practices, for example regulation and control well-drilling, water abstraction and groundwater pollution practices.

In Yemen, policies to boost agriculture have brought higher water demands. Agriculture is the nation's largest user of water. Irrigation accounts for 88% of water consumption in Yemen, followed by urban uses (10%) and industrial uses (2%) (Hellegers *et al*. 2008). Basin irrigation (efficiency ∼40%) is found throughout Wadi Zabid in Tihama coastal plain; and the use of modern irrigation techniques is rare. Large quantities of water are lost, as return flows are unrecovered and mainly discharged directly into the sea. In addition, a large part of the fraction consumed is non-beneficial (Gleick, Christian-Smith, and Cooley 2011), being lost to evaporation from basin irrigation areas due to the high temperatures, which reach 40 °C in the study region. The greater water demand and high water losses have led to accelerated well drilling and construction of many new dams and water diversion structures. Throughout Yemen, lands irrigated from wells expanded tenfold from 1970 to 2008, from 40,000 ha to 400,000 ha, and the number of wells rose from just a few thousand to 50,000 over the same period (Hellegers *et al*. 2008). According to FAO [Food and Agriculture Organization] (2009), there were about 347 storage dams and 33 diversion structures. During the last thirty years, some sixty dams have been built in the western mountain region of the country (Charbonnier 2009).

Tihama plain, on Yemen's western coast, is one of the regions facing a severe water crisis. Groundwater levels here have been dropping for decades, and water quality has also diminished, due to rising salinity among other reasons. There were about 12,600 wells in Tihama plain in the mid-1980s, the annual drop in groundwater levels was 0.9 m in agricultural areas, whereas the average annual drop was 0.4 m for the whole Tihama plain (TSHWC [Technical Secretariat of the High Water Council] 1992).

Wadi Zabid, the study area, is one of eleven wadis that drain into the Tihama coastal plain, a fertile region characterized in the past by its shallow groundwater. To meet the growing water demand for fruit cultivation (bananas, mango, papaya, watermelons) and vegetables, thousands of wells have been drilled throughout the Tihama region. According to Al-Qubatee *et al.* (2017), stakeholders in the coastal area of Wadi Zabid observed that groundwater levels were less than one meter below the soil surface (mbss) prior to the 1970s, while by 2013, the level had dropped to more than 12 mbss with higher water salinity in a few wells. The electric conductivity (EC), which is an indicator of total dissolved solids in groundwater and hence of quality, varied between 0.8 and 17.8 dS/m (NWRA [National Water Resources Authority] 2009). This is much higher than the standard EC for drinking water, which is 0.2–0.8 dS/m. Stakeholders in the coastal, downstream and midstream areas ranked the leading causes of groundwater depletion as follows: (i) lack of rainfall, (ii) construction of dams and water diversion structures, (iii) changes in cropping patterns and low irrigation efficiency and (iv) random drilling of wells with over-abstraction of groundwater.

A requirement for sustainable groundwater management is an understanding of the influence of both natural, or climatic, conditions and the effects of previous management decisions and policies (Thomas and Famiglietti 2015). As Li, Li, and Endter-Wada (2017) pointed out, water resources management concerns a complex and interrelated human and natural system. Water managers therefore need to base their activities on research studies grounded in integrative approaches and use collaborative and interdisciplinary frameworks that systematically incorporate multiple perspectives and experiences. For such studies, hydrological, hydro-meteorological data and land cover maps are invaluable, particularly series of such data over time. Analyses based on monitoring and recording can help decision-makers to better understand the situation in a region and to monitor changes over time. For example, by using a series of land cover maps, the impacts of past management decisions on a landscape can be identified to improve future decisions (Skole *et al.* 1997; Rindfuss *et al.* 2004; NOAA website https://oceanservice.noaa.gov/facts/lclu.html as of April 19, 2020). Remote sensing is a useful technology to obtain such data, especially in low-income countries where continuous and reliable data are not always available or field studies are costly. Also, understanding the rainfall-runoff (surface water inflow) relationship and analysis of past hydrological data (changes in natural runoff patterns) is tremendously important to assess the impact of the human, social and economic activities on the hydrological cycle (Terakawa 2003).

Most previous work on groundwater depletion has focused on either natural or human-induced factors; few studies have focused on both types of drivers. Moreover, within this literature, many authors have examined the drivers of depletion, without considering cumulative effects or drawing links with government policy measures and the resulting changes in human activities. Examples of studies investigating partial drivers of groundwater depletion in Tihama plain are Al-Qubatee, Hellegers, and Ritzema (2019); Al-Qubatee *et al.* (2017); Nasher, Al-Sayyaghi, and Al-Matary (2013); Almhab *et al.* (2012); Almhab (2011); World Bank (2009); NWRA (2009); NWRA (2008); Abu-Lohom (2002); Al-Kebsi (2000) and Al-Eryani (1979). According to Graham *et al.* (2020), future studies are needed that analyze where and why human interventions can reduce water stress in the future, together with climate changes studies. The current research expands on past work by considering both natural and human-induced drivers of groundwater depletion and linking human activities to government policy measures, thus offering a more integrated and comprehensive analysis. This perspective was applied to examine the main causes of the huge drop in groundwater level in Wadi Zabid. Our combined perspective provides a more complete picture of the contributions of various factors to groundwater depletion.

To assess the drivers of groundwater depletion in Wadi Zabid, Yemen, we combined locally sourced and remote sensing data. Four research questions were posed: (1) Was there a decrease in rainfall and runoff (surface water inflow) in the 1970–2009 period? (2) To what extent has agriculture expanded? (3) What changes can be observed in the rate of well drilling, groundwater abstraction and levels and construction of water harvesting and diversion structures during the 1970–2009 period? (4) Is there a relationship between groundwater depletion and water and agricultural governmental policies?

The novelty of this study is that it considers natural as well as human-induced drivers of groundwater depletion based on time-series analysis. It also links changes in human activities to government policy measures, so as to identify the main causes of groundwater depletion, thereby advancing current work in this field.

2. Study area

The study area[2] is part of the Tihama coastal plain, which represents one of the important groundwater aquifers in Yemen thanks to the thick alluvial deposits through which runoff from the wadis percolates to replenish groundwater stores. Agriculture is the main activity in the region, in addition to livestock grazing and fishing. Agriculture is concentrated in three seasons: the summer season, from mid-March to the end of June; the autumn season, from July to the end of September; and the winter season, from October to the end of December (Personal communication, Al-Nashery, Agricultural Specialist, 12 May 2017). A variety of crops are cultivated: cereals (sorghum, pearl millet and maize), oilseed (sesame), fruit (bananas, dates palms, mangos, watermelons, papaya, cantaloupes, guava and citrus), vegetables (tomatoes, onions, okra, legumes, zucchini, hot peppers, mulukhiyah), fodder and others such as cotton and flowering plants (Jasminum sambac and henna).

Wadi Zabid is one of the most fertile catchments of the Tihama coastal plain. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate and continues through Al-Jarrahi, Zabid and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years (Figure 1). The wadi is about 140 km long. Most of its length, 94 km, is in the upstream mountainous areas, with the remaining 46 km in the Tihama plain. The total catchment area of the wadi is about 4,450 km^2 (Van der Gun and Ahmed 1995; Qaid 2007). For the purposes of the current study, the Tihama plain is divided into three areas: (i) the midstream of the wadi, which is the area from the foothills to weir 5 and the lands irrigated by these weirs; (ii) the downstream of the wadi, from weir 5 to the center of Al-Tuhita directorate; and (iii) the coastal area, from the center of Al-Tuhita directorate to the Red Sea coast.

Rainfall amounts vary along the wadi and from year to year. Rainfall is greatest in the mountainous areas, averaging 550 mm/yr, decreasing to 350 mm/yr in the midstream area and 100 mm/yr near the coast. The rainy season, when the floods come, extends from the end of March until mid-October (about 204 days) followed by a dry

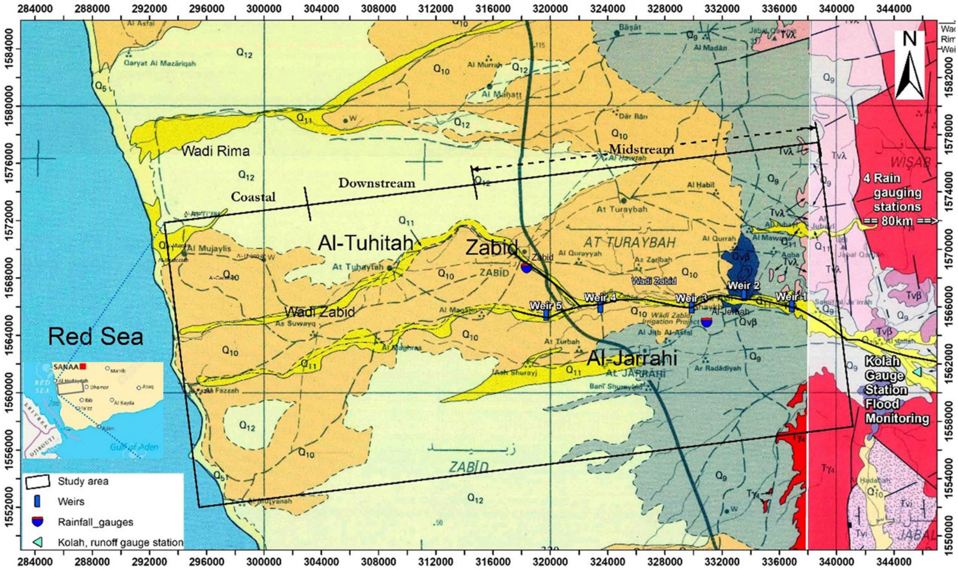

Figure 1. Geologic map of Wadi Zabid showing the division of the study area into midstream, downstream and coastal areas. Extracted from Al Hudaydah sheet 14F and Dhamar sheet 14G, 1:250,000 (Robertson Group 1991).

season with only base flow, from mid-October until the end of March (about 161 days).

Average temperatures range from 18° to 40 °C (NWRA 2009). The average potential evaporation is about 3,000 mm/yr (TDA [Tihama Development Authority] 2010), which is high and exceeds rainfall amounts. The mean relative humidity is 66%, and the mean wind speed is 1.7 m/s at the Al-Jerbah meteorological station in the midstream area of the wadi (TDA 2010). The average annual water flow in the wadi from 1970 to 2009 was 122 Mm^3, recorded at Kolah gauging station (DHV [Dwars, Heederik en Verhey] 1988; TDA 2010). In the study area, irrigation depends mainly on groundwater, in addition to scarce rainfall, except in the midstream zone where spate irrigation is also used.

In the late 1970s, the Government of Yemen sought to encourage agricultural production through the construction of water harvesting and diversion infrastructure. Currently there are 22 dams upstream in the wadi (Personal communication, A. A. Almhab, Ministry of Agriculture and Irrigation, 25 January 2015). In the past, farmers in the midstream area built temporary earthen diversion structures and canals prior to every flood season to distribute spate waters. In 1979, these temporary structures were replaced by five permanent weirs and an associated network of irrigation canals (some 123 km in total length) to irrigate 15,200 ha (Bahamish 2004). Distribution of spate water in the midstream of the wadi is governed by the traditional “Al-Jabarti rules,” introduced by Shiekh Ismail Al-Jabarti more than 600 years ago. The rules are based on the “*al ‘ala fa al’ ala*” principle; that is, the upper riparian zone has first priority for spate water use, with spate waters further shared among three midstream groups. The spate water is thus divided between three groups in the midstream area. Group one, which includes the lands located beyond weir 1 and weir 2, have spate water rights from 19 October to 2 August (288 days), with a mean water allocation of

80 Mm^3, to irrigate 4,805 ha. Group two, which includes the lands beyond weir 3 and weir 4, have spate water rights from 3 August to 13 September (42 days), with a mean water allocation of 32 Mm^3, to irrigate 10,175 ha. Group three, representing the lands beyond weir 5, have spate water rights from 14 September to 18 October (35 days), with a mean water allocation of 17 Mm^3, to irrigate 1,450 ha (Tipton and Kalmbach 1974; Bahamish 2004; IIP [Irrigation Improvement Project] 2005). The rules include detailed provisions concerning water use and distribution within each group. For example, it is prohibited to irrigate land more than once every 14 days. It is also prohibited to reclaim new land or build canals to lands that did not previously have spate water rights (Bahamish 2004). Excess water flows to the downstream and coastal areas. Runoff reaches the sea only after extreme rainfall events, which hardly ever occur (Tesco-Viziterv-Vituki 1971).

3. Materials and methods

3.1. Rainfall-runoff relationship

This research investigated whether the observed fall in groundwater table in the study area was due to decreased rainfall and runoff (surface water inflow). The rainfall and runoff records were investigated over the 1970–2009 period. The topography (elevation) and climate (rainfall) varied from upstream to downstream in the wadi. Upstream rainfall data were recorded at four gauging stations, and midstream data were taken from two stations (Figure 1). Runoff was measured monthly at the catchment outlet, at the Kolah gauging station. The data were collected from the Tihama Development Authority (TDA) and from the literature (e.g. DHV 1988). An excel spreadsheet was developed for data analysis.

To assess trends in rainfall-runoff over the 1970–2009 period, a three-step approach was used: (i) the median of the rainfall records from the upstream gauging stations was calculated on an annual basis and likewise for the midstream area, as the median is a more accurate than the arithmetic average in cases where the data includes extreme (high or low) values (de Nijs and Klausen 2013); (ii) the relationship between rainfall and runoff was established for the upstream region over the 40-year study period, with linear trend lines derived to trace changes in rainfall and runoff; (iii) the relationship between the annual runoff coefficient (K) and rainfall records was established to better understand the rainfall-runoff relationship and the effect of other factors on the runoff coefficient. The runoff coefficient (K) (Equation (1)) was defined as the ratio between runoff (surface water inflow to midstream) and rainfall in upstream and is dimensionless (Critchley, Siegert, and Chapman 1991):

$$\text{Runoff coefficient (K)} = \frac{\text{Annual runoff (mm)}}{\text{Annual rainfall (mm)}} \tag{1}$$

The runoff coefficient is used to compare catchments in terms of their capability to generate runoff (Van der Gun and Ahmed 1995; Blume, Zehe, and Bronstert 2007). In our study, the (K) was calculated based on rainfall-runoff records for the 40 yr (1970–2009), to study the effect of other factors (e.g. the land use/ land cover) on calcuated (K) values for the same catchment area. Runoff is influenced by multiple factors, such as interception of rainfall by land cover, depression storage (natural or artificial, e.g. dams) and infiltration (dependent on, e.g. soil permeability, land slope and artificial barriers such as gabions and water diversion structures). In addition, the high temperatures of the region, particularly in combination with intensive agriculture, led to substantial evaporation and evapotranspiration, due for example, to open irrigation canals and dam reservoirs.

As the 40 years of runoff coefficients represent the same watershed (same soil type and same slope), they provide a good indicator of the driving forces that underlie low or high annual runoff. The question we asked was straightforward: Is low or high annual runoff caused by low or high rainfall or are other factors at work, such as changes in land cover (vegetative cover), due to changes in human activities such as agricultural practices or/ and water harvesting? No complicated rainfall-runoff model was used, as our question could be answered by means of the sample (Anderson, Woessner, and Hunt 2015) since both rainfall and runoff records were available (Seibert 1999).

3.2. Remote sensing and ArcGIS

This study used remote sensing technology (satellite image) to investigate the extent of the agricultural expansion in the study region. Satellite images represent an invaluable resource for monitoring land cover changes over decades. They provide detailed, precise, time-saving and cost-effective information (Forkuor and Cofie 2011). Thus, remote sensing can play a key role in land and water management (DHV 1987).

The Landsat image series from the US Geological Survey capturing over 42 years was used. The images selected were those taken in December of 1972, 1984, 2009 and 2014. These years were carefully chosen to offer as high a resolution as available, especially in the earliest years) to detect changes in land cover associated with major events in the country. The images have a 30 m spatial resolution and 16-day temporal resolution. The ArcGIS Pro classification wizard and pixel-based classification employing the support vector machine (SVM) algorithm were used to analyze the remote sensing images. ArcGIS Pro is a classification wizard developed by the Environmental Systems Research Institute (ESRI) to guide users through the entire classification workflow. According to ESRI, it combines best practices in a simplified interface to efficiently guide users through the classification process. A training sample and supervised classification were used to create land cover maps and detect land cover changes in the selected years. Land cover was categorized in four classes: rocky land, bare soil, agriculture (vegetation) and desert.

3.3. Well inventories

To investigate changes in the rate of well drilling and groundwater abstraction and levels during the 1970–2009 period, we used data from available well inventories and historical sources, spanning local and former government authorities and private companies. The well inventories were carried out in 1972 (Tesco-Viziterv-Vituki as cited in Tipton and Kalmbach 1980), 1975 (Tipton and Kalmbach 1980), 1987 (DHV 1988) and 2008 (NWRA 2008). In addition, a field survey of well water levels was carried out in mid-2016 (Al-Qubatee, Hellegers, and Ritzema 2019). The well inventory carried out in 1975 (Tipton and Kalmbach 1980) did not include abstraction rates. These were estimated on the basis of annual pumping hours, and well yields were calculated as the average of the results of pumping tests carried out by Tesco-Viziterv-Vituki (1973) for 15 wells in the midstream and downstream areas of Wadi Zabid. Abstraction volumes were missing for some wells in the well inventory carried out in 2008 (NWRA 2008) so for these average were taken from nearby wells.

The average groundwater levels in 1972 for midstream, downstream and the coastal area were obtained from the available contour map of groundwater levels. The average groundwater levels in 1987, 2008 and 2016 were obtained from the contour maps of groundwater levels (Figure 1.1A–C, Online Appendix) which were drawn, for the purpose of this study, using the kriging interpolation method (point kriging, using the default linear variogram model in Surfer 9, Golden Software) based on well inventories data, the above-mentioned references. Because the aquifer in the study area has lithological layers extending along the study region (with different thicknesses) according to a geoelectric cross section of Wadi Zabid (DHV 1988), the groundwater level for the whole study region was represented by the average groundwater level of the three parts of the study region (midstream, downstream and coastal).

3.4. Timeline of policy measures related to water and agriculture

To investigate the relationship between groundwater depletion and water and agricultural policies, data on government policies for agricultural development in the region were collected based on the literature review. Thus, a historical timeline was established showing major policy decisions related to water and agriculture in Yemen over time. Major changes (events) in agriculture, such as land expansion or contraction were noted on the timeline, as well as major changes in water resources, such as changes in the rate of well drilling and changes in groundwater abstraction. The timeline therefore reveals linkages between major government policies (drivers), infrastructure development and impacts on the environment. Key political decisions include various laws and legislation enacted, such as subsidized diesel fuel, a ban on agricultural imports or exports, and facilitated imports of drilling and pumping equipment. Infrastructure development consisted mainly of agricultural schemes and water harvesting and diversion structures. Environmental impact was represented by the depletion of groundwater aquifers. The end goal of the exercise was to inform and better rationalize future decisions on land and water management (Mustard *et al*. 2004).

4. Results

4.1. Rainfall-runoff relationship

Over the 40 years under study, a slight increase in rainfall was recorded upstream, alongside a slight decrease in runoff, according to the trend line, linear function (Figure 2A). Thus, less runoff (surface water inflow) reached the midstream area of the wadi. Here, two periods can be distinguished. In the first period, 1970–1979 (Figure 2B), there was an increase in rainfall upstream over time, resulting in a very high increase in runoff. In the second period, 1980–2009 (Figure 2C), there was a slight increase in rainfall upstream over time; however, this was accompanied by decreased runoff.

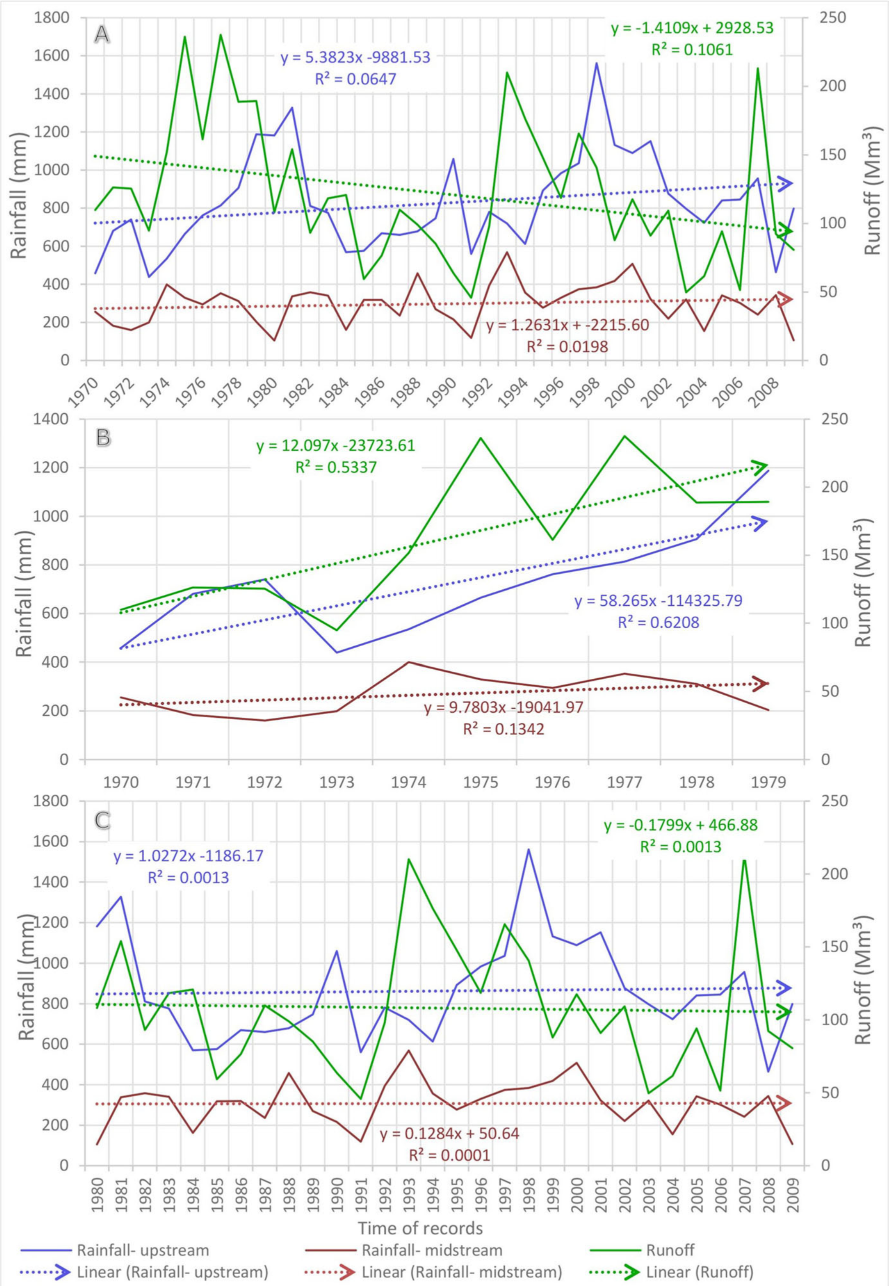

Figure 2. Median annual rainfall, (A) over the period 1970–2009, (B) over the period 1970–1979, and (C) over the period 1980–2009, in the upstream and midstream areas and the runoff (surface water inflow to midstream area).

In the midstream area, similarly, a slight increase in rainfall was recorded over the 40 years, as well as in the first and second periods (Figure 2A–C). The increase was more or less the same as that registered in the highlands. The trend line for both

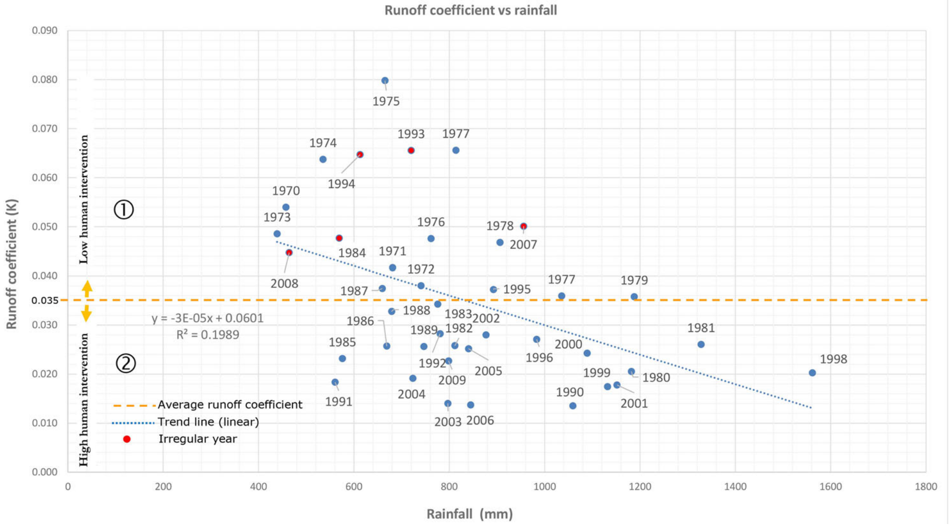

Figure 3. Relationship between the annual rainfall in the upstream area and the resulting runoff coefficient. Two periods can be distinguished. Period 1, the years from 1970 to 1979, comprises the years characterized by a high runoff coefficient (K), meaning high runoff, likely due to limited human intervention. Period 2, the years from 1980 to 2009, comprises the years characterized by a low runoff coefficient (K), meaning low runoff, likely because of human intervention. Five irregular years over the 40-year period were observed (1993, 1994, 2007, 1984 and 2008) which deviate from these characteristic distributions. Overall, the trend of the runoff coefficient (K) is decreasing with an increasing amount of rainfall. This indicates the reduction in the runoff due to a high water use upstream associated with increased harvesting by dams, diversion structures and agricultural activity after 1979.

rainfall and runoff indicates a very low coefficient of determination (R^2), as the amounts of rainfall and runoff were highly variable.

This is clearly demonstrated by Figure 3, which plots the annual runoff coefficient (K) against rainfall. In that figure, the two periods can also be distinguished, based on the average runoff coefficient, which was 0.035 (standard deviation 0.017):

- In period 1, from 1970 to 1979, the runoff coefficient (K) was high (>0.035), regardless of whether the amount of rainfall was high or low. This means there was high runoff in these years, due to limited human intervention (i.e., less agricultural development).
- In period 2, from 1980 to 2009, the runoff coefficient (K) was low (<0.035), again, regardless of whether the amount of rainfall was high or low. This means there was low runoff in these years, due to the substantial human intervention in this period. Particularly, there was an increase in the agricultural area (and thus high evapotranspiration) and an increase in the numbers of the water harvesting and diversion structures (again, leading to high evaporation and reduced runoff). These are associated with the changes in government policies and political decisions (e.g. subsidies on diesel fuel and a fruit import ban) aimed at boosting agricultural production and improving farmers' incomes.

Note that a number of irregular years were observed (1984, 1993, 1994, 2007 and 2008) that deviate from these characteristic distributions, but these can be considered very few.

The trend for the runoff coefficient (K) is decreasing with an increasing amount of rainfall. This indicates that runoff did not increase with increased rainfall as expected (Equation (1)). But, on the contrary, the reduced runoff was likely due to factors such as a high water use upstream associated with increased water harvesting and diversion infrastructures (dams and weirs) and intensified agricultural activity after 1979. This reduced the amount of spate water available for irrigation in the midstream and downstream areas, increasing dependence on groundwater here.

The monthly runoff figures closely track monthly rainfall averages upstream; in other words, every rainfall episode upstream produced runoff at the outlet (Figure 4). The average annual runoff was 122 Mm^3.

In the midstream area, rainfall tended to slightly increase over the 40 years, measured at the two rainfall gauging stations (Figure 2), but average rainfall over the 40 years was very low (only 297 mm/yr). For comparison purposes, rainfall upstream was about four times that in the midstream of the wadi (average rainfall upstream over the 40 years was 827 mm/yr). Despite the large differences in rainfall between the upstream and midstream areas, the ratio between them remained approximately constant over the 40 years. In both the upstream and the midstream areas, the wet season started in April and reached its height from May to October (Figure 4). Yet, runoff reaching the downstream areas dwindled, due to the five diversion structures built midstream. As noted earlier, spate waters were distributed via traditional rules among three groups in the midstream area of the wadi. Only water that exceeded the needs of these groups flowed downstream, and this rarely reached the coast.

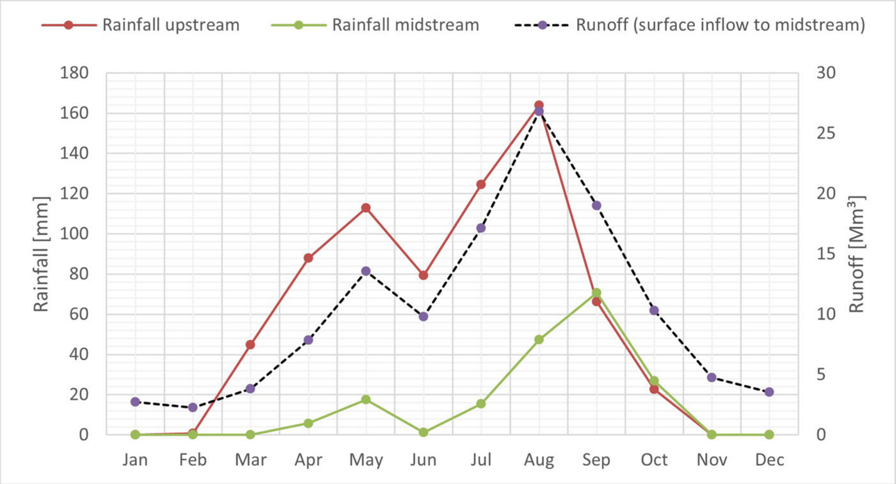

Figure 4. The median monthly rainfall over the period 1970–2009 in the upstream and midstream area and the average monthly surface runoff (surface water inflow to midstream) for same period.

4.2. Land cover

Four land cover classes were identified: rocky land, bare soil, agriculture (vegetation) and desert (Table 1). From 1972 to 2014, three periods were distinguished:

- From 1972 to 1984 there was an increase in agricultural land (46.5%) from 103.8 km^2 to 152.0 km^2. This expansion was associated with a reduction in bare soil cover.
- From 1984 to 2009 there was a large expansion of agricultural land (85.9%) from 152.0 km^2 to 282.6 km^2, alongside a substantial reduction in bare soil and desert cover and a small reduction in desert cover.
- From 2009 to 2014 there was a slight decrease in agricultural land (4.2%), from 282.6 km^2 to 270.9 km^2, alongside an increase in bare soil and a decrease in desert cover.

4.3. Numbers of wells, abstraction rates and groundwater levels

The number of operating wells in Wadi Zabid was 263 in 1972, with about 47.5 Mm^3 of annual abstraction (Tesco-Viziterv-Vituki as cited in Tipton and Kalmbach 1980) (Table 2, Figure 5A). Three years later, in 1975, the number of

Table 1. Land cover classes and distribution, registered in Dec (1972, 1984, 2009 and 2014).

	Dec (1972)		Dec (1984)		Dec (2009)		Dec (2014)	
Class	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Bare soil	374.7	41.0	315.6	34.5	246.7	27.0	298.2	32.6
Desert	408.1	44.6	423.2	46.3	362.5	39.7	311.8	34.1
Rocky land	27.6	3.0	23.5	2.6	22.1	2.4	32.4	3.5
Agricultural land	103.8	11.3	152.0	16.6	282.6	30.9	270.9	29.7
Total	914.1	99.9	914.2	100	914.0	100	913.2	99.9

Total land area is smaller than the rectangular study domain because small parts are located in the Red Sea (Figure 1). In addition, a minor errors result from the low resolution of the Landsat images (e.g. clouds effects). Agricultural lands are less than in actuality due to our selection of Landsat images for December. These only available images with a good resolution for the selected years especially the earliest years. However, cereals are not usually cultivated in December.

Table 2. Operational drilled wells, groundwater levels and abstraction rates in the study area of Wadi Zabid, 1972–2016.

			Groundwater levels (mbss)			
Years	Cumulative numbers of operational wells	Abstraction (Mm^3/yr)	Coastal area	Downstream	Midstream	Whole region
1972[1]	263	47.5	0.5	8	20	9.5
1975[2]	831	81.7	–	–	–	
1987[3]	1221	240.6	10	40	25	25
2008[4]	4250	444.2	18	75	30	41
2016[5]	–	–	35	90	50	58

Sources: Data analysis for the purpose of this study based on 1. Tesco-Viziterv-Vituki (as cited in Tipton and Kalmbach 1980), 2. well inventory 1975 (Tipton and Kalmbach 1980), 3. well inventory 1987 (DHV 1988), 4. well inventory (NWRA 2008) and 5. Field survey in 2016 (Al-Qubatee, Hellegers, and Ritzema 2019).

operating wells had increased to 831, with 81.7 Mm^3 of abstraction, according to the well inventory carried out in that year (Tipton and Kalmbach 1980). The number of operational wells reached 1,221 in 1987 and 4,250 in 2008, with respectively, 240.6 Mm^3 and 444.2 Mm^3 of abstraction, according to DHV (1988) and NWRA (2008). From 1972 to 1975, 189 wells per year were drilled, with 144 wells per year added between 1987 and 2008. There was, thus, a significant increase in well numbers and groundwater withdrawals. As a result, groundwater levels fell by an average

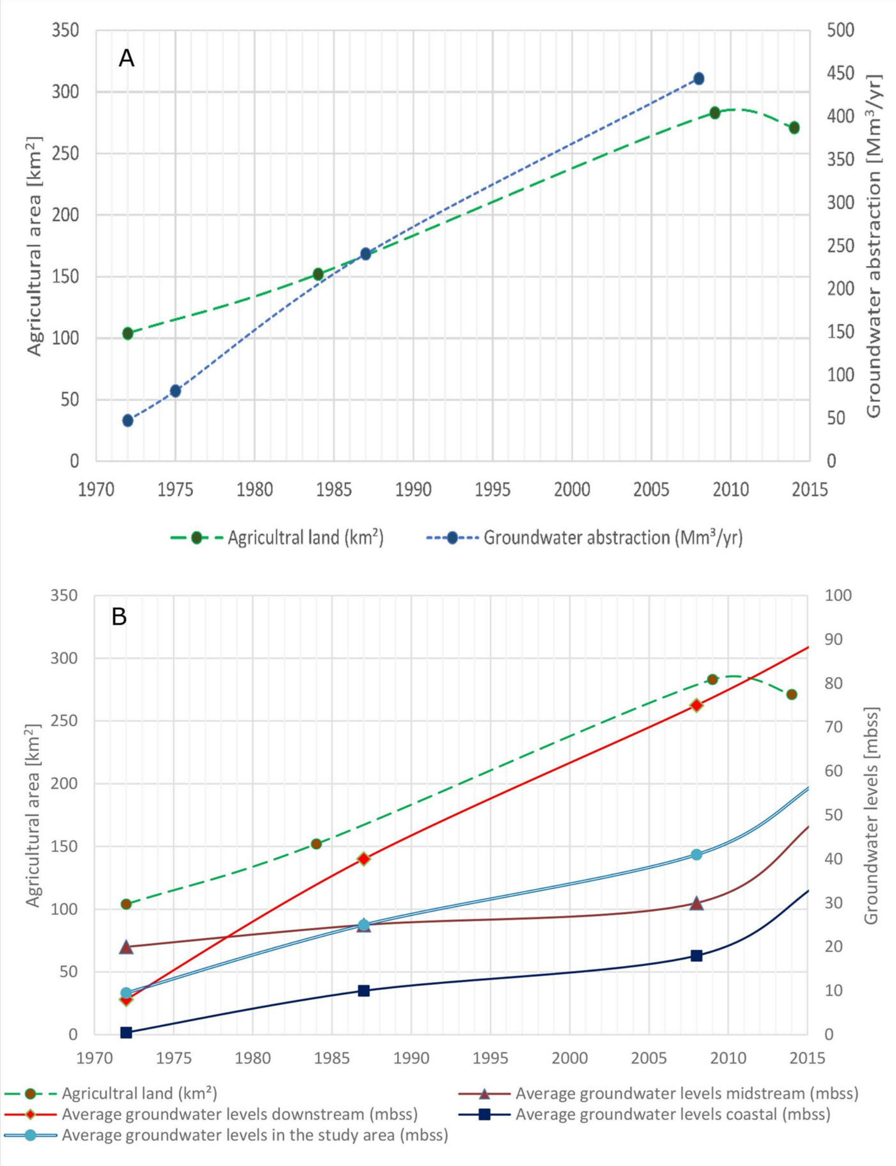

Figure 5. (A) Changes in agricultural land and groundwater abstraction for the whole study region over the 1972–2009 period. (B) Changes in agricultural land and groundwater levels for the midstream, downstream and coastal areas of the study region as well as for the whole study region over the 1972–2009 period (all derived from Tables 1 and 2).

of almost 50 m from 1972 to 2016 across the wadi (Table 2, Figure 5B). Severe groundwater depletion was experienced downstream, followed by the midstream and coastal areas. According to the well inventories and field measurements (Table 2 and Figure 5B), average groundwater level depths in these areas were, respectively, 8 mbss, 20 mbss and 0.5 mbss in 1972. But recently, in mid-2016, groundwater level depths had dropped to 90, 50 and 35 mbss, respectively. The trends in expansion of agricultural lands (Table 1) and groundwater abstraction (Table 2) exhibit a parallel relationship (Figure 5A), especially after 1980. This underlines the increasing over-reliance on groundwater for irrigation over time. In 2014, there was a decrease in agricultural land. However, no data was available on the rates of groundwater abstraction in that year.

4.4. Timeline of policy measures related to water and agriculture

Since 1970, the government has initiated a number of programmes to support farmers by enacting favorable legislation and developing infrastructure to facilitate irrigation and agriculture (Figure 6). These programmes have acted as an incentive to farmers throughout the country, and in the study area in particular. For example, a subsidy on diesel fuel was implemented in 1970, which facilitated public and private investment in well drilling and the import of related equipment. In 1975, the Cooperative and Agricultural Credit Bank was established, giving agricultural entrepreneurs access to investment capital. In 1979, an irrigation scheme was developed in the midstream area of the wadi, with the construction of five weirs and associated canals. Twenty-two dams were built further upstream in subsequent years. Finally, a ban on fruit imports was enacted between 1984 and 1995 to promote local cultivation. After 2011, there was a diesel crisis due to the onset of political change.

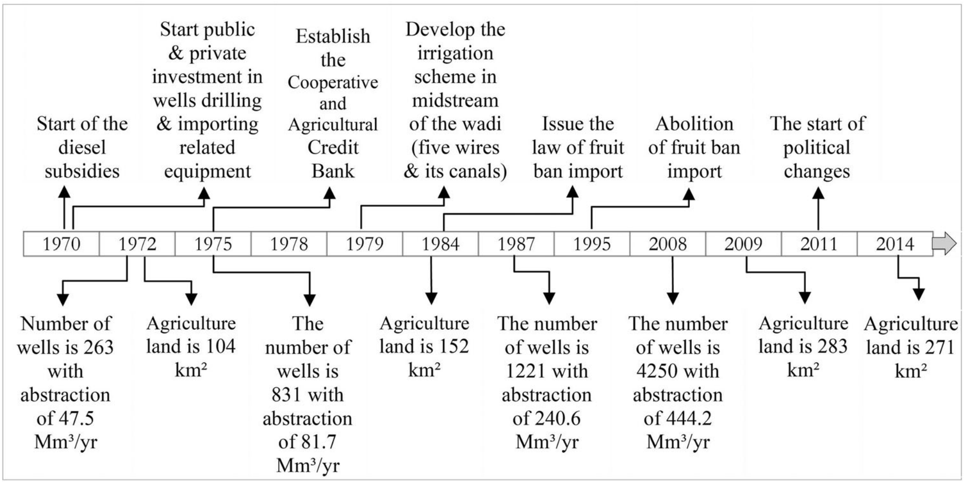

Figure 6. Timeline showing Government policy and the resulting agricultural developments and groundwater abstraction in the study area. Source: the information is based on the result of this study (see Table 1 and 2) and literature review Al-Qubatee *et al.* (2015) and Hellegers *et al.* (2008).

5. Discussion

Over the 40 years under study, rainfall actually increased on average, albeit only slightly. This increase is evident in our rainfall time series data from 1970 to 2009, in both the upstream and midstream areas of the wadi. However, the runoff (surface water inflow), reaching the midstream area decreased. It is notable that early in our study period, from 1970 to 1979, very high runoff was measured, associated with high rainfall. After 1980, runoff reaching the midstream area decreased, despite increased rainfall upstream. Increases in rainfall are projected to continue in Yemen. A rise of about 15–20% is expected over the 2020–2050 period, relative to the benchmark, which is 2000–2009, according to climate data for the Middle East by Terink, Immerzeel, and Droogers (2013).

A number of human interventions reduced the amount of runoff that reached the downstream areas. Most important among these was the expansion of agricultural lands, in particular land planted with cash crops which have high water demands. The remote sensing data (satellite images) analyzed confirm, for the study region, the significant expansion (172%) in land area under agriculture between 1972 and 2009. Van Steenbergen *et al*. (2010) found that banana farming in the midstream area of Wadi Zabid had expanded from 20 ha in 1980 to 3,500 ha in 2000. In addition, the Irrigation Improvement Project (IIP) (2002) confirmed that high-value crops, such as vegetables (e.g. onions, okra and tomatoes), and cash crops (e.g. bananas), were replacing traditional crops (e.g. sorghum, sesame and cotton). Irrigation water application for bananas in Wadi Zabid is very high: about 40,800 m^3/ha per year (Al-Qubatee, Hellegers, and Ritzema 2019). This high water demand was accommodated by increased well drilling and high groundwater abstraction rates. This reality is dictated by circumstances in most cases: humans respond to drought and water scarcity by deepening dried-up wells and building dams, despite the negative environmental consequences (Famiglietti 2014; Zetland 2014). This clearly emerged from our study, in the huge rise in well drilling and water abstraction rates. The number of operating wells in the study region increased from 263 in 1972 (Tesco-Viziterv-Vituki as cited in Tipton and Kalmbach 1980) to 4,250 in 2008 (NWRA 2008), with annual abstraction growing from about 47.5 Mm^3 to 444.2 Mm^3 in this period. As a result, groundwater levels fell by an average of almost 50 m from 1972 to 2016 across the wadi.

In addition, construction of water harvesting and diversion structures after 1979 reduced runoff. According to Van der Gun and Ahmed (1995), in conditions such as those in Yemen, many factors influence runoff, such as catchment size and shape, rainfall, evaporation and evapotranspiration, terrain characteristics (slope, presence and characteristics of soil, rock outcrops), the groundwater system, land cover and land use (agriculture terracing, dams, spate irrigation systems and any other human intervention). In our study, the low runoff (surface water inflow) reaching the midstream area was a clear consequence of human activity upstream. Other factors that affected runoff were relatively constant in our study, as our analysis of rainfall and runoff considered just one area over time. That is why a slight decrease in the runoff coefficient was observed, despite the increase in rainfall. A study by Grum *et al*. (2017) found a decreased runoff coefficient for the Gule catchment and Misbar sub-catchment, in northern Ethiopia, due to the building of water harvesting techniques. The average, per event, reduction in runoff was estimated as 41% and 45% respectively. According to Bahamish (2004), construction of these concrete structures and changes in agricultural practices have contributed to a violation of the traditional spate water distribution rules; with these changes, the rules are no longer able to achieve fair spate water distribution. Here, human interventions were responsible for the reduction in runoff reaching downstream areas. Similar trends were observed in a study of the Zhuoshui River in Taiwan, in which Tsai *et al.* (2016) found that weir operations substantially affected water resources. Increased weir discharge resulted in increased groundwater levels, by about 0.1 m annually.

Our results suggest a strong link between groundwater depletion and political decisions related to water and agricultural resources. Thus, human factors were evident, not only through the practices and activities observed within the study area but also in the government policies and political decisions that acted as an engine and catalyst (driver) for them. The timeline demonstrates that the increased area devoted to agriculture was propelled on the supply side both by the increased water availability (from wells and dams) and by political decisions related to water and agriculture. In other words, political decisions had the unintended effect of groundwater depletion. Examples of impactful decisions are the establishment of a subsidy on diesel fuel starting in 1970, facilitation of public and private investment in well drilling and import of related equipment, creation of a bank in 1975 to provide credit for agricultural activities, construction of dams after 1979 and the banning of fruit imports from 1984 to 1995. These political decisions boosted agricultural activities, hence improving farmers' incomes and creating local job opportunities (e.g. for exporters of agricultural products). However, they had negative impacts on water resources. In particular, many farmers switched from food security crops with low irrigation requirements to cash crops with high irrigation requirements. The leap in the number of operational wells, from 1,221 to 4,250, and expansion of agricultural lands, from 152.0 km^2 to 282.6 km^2, between 1984 and 2009, occurred after the 1984 enactment of the ban on fruit imports.

Hellegers *et al.* (2008) and Al-Weshali *et al.* (2015) attributed the large increase in groundwater pumping rates for cash crop irrigation to government policy, particularly subsidies on diesel fuel. Policies and legislation acted as an incentive for agricultural expansion, reducing the cost of agricultural inputs and increasing the price of agricultural outputs. Numerous studies make similar observations on this theme. Hellegers *et al.* (2008) and World Bank (2010) recommended reorienting economic and other incentives toward reducing water demand. In addition, policies and regulations are needed to stem the depletion of groundwater resources. The current availability of water resources, paired with the incentives mentioned above, encourages farmers to switch to more fruit crops (Hellegers, Perry, and Al-Aulaqi 2011). This study found a slight contraction of cultivated land area, by 4%, from 2009 to 2014, likely associated with the diesel crisis as a result of the unstable political situation after 2011. According to Al-Weshali *et al.* (2015), the instability after 2011 led to a fuel crisis and thus to substantially higher prices. This slightly eased the stress on groundwater, also reducing depletion rates. But it has increased economic hardship and significant losses of income for farmers, affecting their food security and livelihoods (Al-Qubatee, Hellegers, and Ritzema 2019).

6. Conclusion

This study demonstrates the value of a research approach combining both natural and human-induced drivers of groundwater depletion. Extending earlier research, most of which investigated partial drivers of groundwater depletion, the integrative framework adopted here provided a clear picture of the contributions of the different drivers to the observed drop in the groundwater table. This study indicates the crucial role that policy measures played in triggering changes in human activities and thus in water use. These results demonstrate the considerable environmental impact of policy measures affecting water use. These impacts need to be factored into future planning decisions.

The current study, based on 40 years of rainfall and runoff data, found that rainfall was not a driver of groundwater depletion in Wadi Zabid. While there was a slight increase in rainfall, this was accompanied by a reduction of surface water flowing from the uplands to the midstream area of the wadi over time. The reduction in surface flows was attributed to the expansion of agricultural land and construction of water harvesting structures. Land use maps of the study region indicate that despite a slight, 4%, contraction of agricultural lands between 2009 and 2014 (likely due to the diesel crisis associated with the unstable political situation after 2011), agricultural area increased significantly between 1972 and 2009. Indeed, agricultural land cover rose from 103.8 km^2 in 1972 to 282.6 km^2 in 2009. That expansion was associated with a leap in the number of operational wells, from 263 to 4,250 over this period. Groundwater abstraction also grew, from 47.5 Mm^3 (Tesco-Viziterv-Vituki as cited in Tipton and Kalmbach 1980) to 444.2 Mm^3 (NWRA 2008). This contributed to a drop in groundwater levels by an average of almost 50 m between 1972 and 2016 across the wadi. Regarding water harvesting and diversion structures, five weirs were constructed midstream in 1979 to divert water for irrigation. This was followed by the construction of more than 22 water harvesting structures (dams) further upstream (Personal communication, A. A. Almhab, Ministry of Agriculture and Irrigation, 25 January 2015).

A clear link was also found between the introduction of policy measures to boost agricultural activities and changes in agricultural activities, irrigation infrastructure and groundwater abstraction over time. Policy measures related to water and agriculture succeeded in increasing agricultural lands and hence increased farmers' incomes. But this came at the expense of groundwater resources. Based on these findings we can conclude that human-induced factors – rather than a lack of rainfall – were the main drivers of groundwater depletion in Wadi Zabid.

As a recommendation, policies and decisions on economic incentives could be oriented to support reallocation of water for lower consumption uses. The role of policy is particularly great in the coastal regions, which are especially vulnerable to seawater intrusion. In such regions, encouraging alternative, less water-consuming income sources is preferable to encouraging cash crop production as a livelihood strategy. The same is true for the midstream and upstream areas, in order to increase runoff and groundwater recharge for the wadi as a whole. Although cash crops may offer higher incomes in the short term, they are detrimental to sustainable livelihoods and food security, due to their greater water consumption. In addition, better management of water in the existing harvesting and diversion structures is needed, alongside greater emphasis on policies that could help to slow the current rapid groundwater depletion rates, such as improved wastewater treatment infrastructure and seawater desalination plants. Moreover, water laws could be implemented to regulate well drilling and abstraction rates. With this in mind, estimation of the economic value of water would be a valuable next research step, to suggest better allocations of scarce water resources, particularly, high value activities with less water requirements.

Notes

1. Land cover, which can be determined by satellite imagery, refers to the vegetation (natural or planted) and/or artificial structures which cover the earth's surface. It also includes water, bare rock, sand and others. Land use reflects human activities on the land, and land cover maps provide an indicator of land uses and vis versa is correct.
2. Geolocation information: Wadi Zabid is one of the catchments of the Tihama coastal plain. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate and continues through Al-Jarrahi, Zabid and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years. This study covered the plains area of the wadi, divided into a midstream, downstream and coastal zone (about 46 km by 20 km altogether). The center of the study region has the coordinates 317,122UTM-E and 1,564,732UTM-N.

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Data availability statement

Data collected from governmental institutions (mentioned in the acknowledgement section) for the purpose of this study. It is a part of PhD study at Wageningen University and Research, and it is available on request from corresponding author.

Authors' contribution

W.A.-Q. (Former PhD Fellow at Wageningen University and Research, graduated in June 2021) conception and design of the manuscript. Carried out the field visit and data acquisition. Data analysis and interpretation. Wrote the manuscript and did critical revision. **F.A.H.** analyzed the remote sensing imagery with writing inputs in the methodology in regard to remote sensing. **H.R.** and **G.N.** supervised the overall research and did critical revision and suggestions for improvement of the content of the paper. **P.H.** the overall supervision of the research and the major critical revisions and the suggestions for improvement of the content of the whole paper.

Disclosure statement

The authors declare no potential conflicts of interest.

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Supplemental data

Supplemental data for this article can be accessed here.

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