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Water accounting in the Berrechid plain (Morocco): a process approach¹

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Abstract

Water scarcity is a growing challenge to the governance of water resources and to multiple water uses. Dealing with water scarcity requires a better-shared understanding of water supply and demand dynamics by different stakeholders who contribute to and/or suffer the consequences of water scarcity. This study highlights the importance of establishing a water accounting system for groundwater management in the Berrechid plain (Morocco) and the conditions under which such accounting may help solve current water issues. The plain is under considerable water stress, and stakeholders are struggling to implement aquifer management plans to ensure groundwater sustainability. The study identified and quantified various components of the water balance and estimated annual groundwater overexploitation for the period 2001-2018 to be 32 million m³. Fractional analysis of the water balance showed that the reason for aquifer water stress was a rapid increase in irrigated land and current intensive agricultural and irrigation practices, which threaten both the sustainability of water resources and economic activities in the plain. To improve water governance, a system of water accounting is required that promotes responsible use and ensures that all stakeholders are answerable and accountable for their water consumption along with any actions that may affect water flows.

Keywords: Water accounting, groundwater, water governance, water scarcity, water balance, Morocco

Résumé

La pénurie d'eau constitue un défi croissant pour la gouvernance des ressources en eau et pour les multiples usagers de l'eau. Faire face à cette pénurie, requiert une meilleure compréhension partagée des dynamiques de l'offre et de la demande en eau par les différentes parties prenantes contribuant à et/ou supportant les impacts de cette pénurie. Cette étude met en évidence l'importance d'établir un

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système de comptabilité de l'eau pour la gestion des eaux souterraines dans la plaine de Berrechid (Maroc) et les conditions dans lesquelles une telle comptabilité peut contribuer à résoudre les problèmes d'eau actuels. La plaine connaît un stress hydrique considérable et les parties prenantes ont du mal à mettre en œuvre des plans de gestion des aquifères pour assurer la durabilité des eaux souterraines. L'étude a identifié et quantifié les différents composants du bilan hydrique et a estimé le volume surexploité des eaux souterraines entre 2001 et 2018 à 32 millions de m³. L'analyse fractionnelle du bilan hydrique montre que l'aquifère est passé à un état de stress hydrique en raison de l'augmentation rapide des zones irriguées et des pratiques agricoles et d'irrigation actuelles intenses, menaçant la durabilité des ressources en eau et des activités économiques dans la plaine. Pour améliorer la gouvernance de l'eau, il est essentiel de mettre en œuvre un système de comptabilité de l'eau qui favorise la responsabilité et garantit que toutes les parties prenantes sont responsables de leur utilisation de l'eau et de toutes les actions susceptibles d'affecter les flux d'eau.

Mots clés : Comptabilité de l'eau, eaux souterraines, gouvernance de l'eau, pénurie d'eau, bilan hydrique, Maroc

1. Introduction

"We never know the worth of water till the well is dry." -Thomas Fuller (1608-1661).

Due to the combined effect of increased water demand and reduced water supply linked to climate change, water scarcity represents a daunting threat to "food security, human health, and natural ecosystems" (Seckler et al., 1999). The threat is manifested in decreasing available resources, widespread overexploitation of groundwater resources beyond their renewal capacity, declining water quality, vulnerability to hazards such as droughts and floods and conflicts between users. These issues are difficult to address in the absence of genuine and continual stakeholder engagement in understanding the current situation and in negotiating remediation strategies to sustainably meet the needs of all water users, including those of the environment (Iglesias et al., 2007).

Water accounting seeks to provide comprehensive, consistent, and comparable information related to water for policy and decision-making to promote the sustainable use of water resources as well as equitable and transparent water governance among water users (Ottaviani et al., 2016). However, such "collaborative institutions" around water governance are time-consuming, and the results are not immediate, which explains why analysts generally consider "watershed collaboration as a kind of last resort when more straightforward governance is impossible" (Ingram, 2011). Water accountability is often described as an explicit objective of water accounting, whereby different actors, including the state, become answerable for their actions (Tello & Hazelton, 2018; Lankford et al., 2020). Of course, holding the different actors accountable "for their water consumption in economic, legal or moral terms" is a major challenge (Paerregaard, 2019: 490). Finding solutions will require the involvement of both water resource managers and water users: "not only must remedies be designed for the context, they also actually must be implemented" (Ingram, 2011: 241). However, dialogue about water is

generally difficult because, first, water resource dynamics, which often combine surface and groundwater, are complex and involve vastly different types and scales of water supply and use. Consequently, policy decisions are often made without a clear understanding of their consequences for all water users (Molden, 1997). In this context, a better and, equally importantly, shared understanding of water dynamics is crucial for the design of effective strategies for water resource management. Second, with increased water scarcity, the water stakes have increased, and painful decisions have to be negotiated between stakeholders to reduce water demand (Mekonnen & Hoekstra, 2016). Third, whereas the state is often seen as a neutral referee, it is – like society – riddled with contradictions, emitting contradictory signals on water use (Kuper et al., 2023). Typically, a farmer may obtain subsidies from the department of agriculture to intensify agricultural production while receiving warnings from the water department to restrict his/her use of water. The lack of institutional coherence in the management of water resources has proven counterproductive in many countries (Pahl-Wostl et al., 2020). Fourth, uneasy access to high-quality information hinders stakeholders' ability to analyse water-related issues and make informed contributions to decision-making processes (OECD, 2015).

Consequently, there is a need for a sound and shared system of water metrics to enhance the understanding of river basins by stakeholders who make decisions concerning the retention, allocation, and release of scarce water resources (Bastiaansen et al., 2014). The question then is not only which data need to be collected but also who decides which data are collected and how the data are treated, analysed and shared. If data and data analysis are not coproduced and widely shared with different stakeholders and the general public to create trust about data and agreement on the analysis of water scarcity, a “downwards cycle of poor accounting and poor water management” is bound to happen (FAO & WWC, 2018: 27).

The present study was conducted in the Berrechid plain in Morocco. As the water in the Berrechid aquifer is already fully committed to different uses, for the past 20 years, there has been a permanent annual water deficit, resulting in a drop in the groundwater table (Ouassissou et al., 2019). Different government agencies, including the river basin agency and agricultural services, have undertaken actions to solve the problem of groundwater depletion. The instruments used or planned to address the unsustainable use of the aquifer include those that target conventional and unconventional water resources in parallel with instruments aimed at reducing water withdrawals by providing subsidies for drip irrigation. These actions have had unforeseen rebound effects such as agricultural intensification and the continuing depletion of groundwater resources due to an ever-widening gap between supply and demand (Ouassissou et al., 2019).

The purpose of this study was to design and discuss a shared water accounting information framework based on the specific case of the Berrechid Plain. The paper highlights the need for shared tools to support policies for better accountability and to improve the governance of water resources. The objective is to demonstrate the relevance of such a framework in understanding the different dimensions of the water balance, specifically, water resources, water consumption and return flows. The possibility of recovering flows to address the chronic deficit is assessed. An approach designed

to institutionalise water accounting as a tool for dialogue between actors to address the current groundwater decline is evaluated.

2. Water Accounting: origin of the concept and approaches

Of course, water accounting has existed ever since people started to observe and manipulate water flows. Water accounting systems vary considerably, operate at different scales, have different objectives and use different methods ranging from the “*hydrologist’s gauging station to the thrifty household’s water meter*” (Babillot & Margat, 1999). Often, such water accounting systems are an indicator of the proprietor’s view of water (see van Halsema & Vincent, 2012, for a wider debate on this view²). Wade (1976:1436) reports, for example, on the water accounting method used by the Maharashtra Irrigation Department (India), which enables its engineers “to have up-to-date information about where exactly the water in their canal is going”. However, in recent decades, there have been several initiatives for a more territorial approach to water accounting to provide a more coherent view of the different uses, services and allocations of water in a given river basin, aquifer system or waterscape (Molden, 1997; Babillot & Margat, 1999). In France, for instance, a regional and national water accounting system was created in 1985 to obtain a better understanding of the balance between available (renewable) water resources and uses (Babillot & Margat, 1999). International organisations, including UNESCO through its International Hydrological Programme (e.g., Shiklomanov, 1998), FAO through its AquaStat database, ICID, the World Water Council, the OCDE and international donor organisations, including the World Bank and Asian Development Bank, progressively became involved in accounting for the world’s water resources and uses, as the notion of water scarcity gained prominence after a long period of water resource development (Meckling & Allan, 2020).

There has been mounting interest in territorial approaches to water accounting with different conceptual advances to address increasingly complex water-related issues, such as identifying water saving opportunities, enabling a better understanding of the impact of present uses and interventions on water flows and different uses, and encouraging dialogue between water professionals and water users alongside better-informed water allocation policies (Molden, 1997). Following the implementation of the European water directive, another main topic in the literature was better accounting for water requirements for environmental reasons, including maintaining wetlands and other important ecosystems (e.g., Pahl-Wostl et al., 2020). Notably, water accounting had to deal explicitly with the issue of scale, linking water use at the household or field level to water dynamics at the irrigation system or basin level. In the agricultural sector, designated by global studies as the principal water user at approximately 80% (Shiklomanov, 1991), the water accounting approach was closely related to the debate around the concepts of irrigation efficiency and productivity and water

² Contextual relativism acknowledges that the merits and limitations of water management concepts vary based on specific contexts and scales. Therefore, a one-size-fits-all approach to water management may not be effective, and instead, a contextualised approach is necessary. This is particularly true in water accounting, where a tailored approach is required for effective water management.

recycling (Seckler et al., 1999). The dilemma is that improving efficiency at the plot level without reducing overall water consumption (typically through more intensive agriculture once drip irrigation is installed) does not necessarily improve efficiency at the basin level (van der Kooij et al., 2013). Indeed, the recycling of water in river basins means that infiltrated water often becomes a resource for other users and hence a shortfall if more water is consumed in a given plot, even if irrigation has become more efficient. There is thus a clear need for a tool that reliably accounts for water resources and their uses at different levels while simultaneously monitoring water recycling (Seckler et al., 1999). In 1996, the International Water Management Institute (IWMI) developed a water balance model that allows the evaluation of water flows in an irrigation project to quantify all inputs, outputs, consumptive use and water recycling. The model defines water losses and predicts the impacts of changes in management or infrastructures on existing balances (Perry, 1996). In 1997, the IWMI published standard terminology and procedures to be used to describe the status of water resource use, making it possible to assess the performance of water use at different scales and levels and the consequences of actions targeting water resources (Molden, 1997). Water accounting helps clarify certain concepts such as water depletion, i.e., a withdrawal of water from a water basin making it unavailable for further use. The most fundamental distinction lies between consumption and abstraction because abstracted water is not 100% consumed. Gross withdrawals are ‘diversions’, while net withdrawals are actual water consumption. In water accounting, the concept of consumption includes not only productive uses of water but also nonproductive uses such as evaporation (from dams and other bodies of surface water or transpiration by plants), water flowing into the sea or into saline aquifers (flows to saline sinks or heavily polluted aquifers), polluted water becoming unusable, and water incorporated into products or consumed by services. The analysis of nonproductive uses makes it possible to identify technically and economically recoverable fractions that can be reused or fulfil environmental functions.

Unlike most common water balances, which only evaluate the flow of water when it enters the economic system, whether it is used, treated, or returned to nature, water accounting is geared towards measuring the complete cycle of water from precipitation to its return to nature via various ecosystems and human consumption, including the assessment of the damage caused if it is polluted along the way (Monzonís et al., 2016). Water accounting can quantify water resources, the performance of water management and governance, and the links between water and economic, human, and environmental development (FAO & WWC, 2018). Today, several integrated water accounting systems are operated by different states and international organisations for a variety of purposes; these systems include the Economic and Environmental Accounting System; the National Water Accounts Australia (AWAS), which has been applied in other countries, including Spain and South Africa (Mombloch et al., 2014); the ‘Water Accounting Plus’ method developed by UNESCO-IHE, IWMI, FAO and UNESCO-WWEP (Ariyama et al., 2019); and the water footprint method (Hoekstra & Hung, 2002), an indicator mapping the impact of human consumption on global freshwater resources.

Despite the multiplication of international water accounting frameworks and initiatives, the approach has not been transformed into practice in the majority of countries. Several challenges to the development and use of water accounting have been reported (Tello & Hazelton, 2018). First, it

requires continuous efforts to establish an open and shared tool for dialogue between actors with different skills and profiles (Camkin, 2016). Second, close attention must be paid to the quality of the data to improve confidence in the data and results (Cordery et al., 2007). Water governance must be analysed in parallel with water accounting to understand the intervention, the actors' dynamics and the links between the decisions made to manage water and the situation of water scarcity (Batchelor & al, 2017). Finally, it is not easy to change the behaviour of water professionals to promote information sharing and transparent dialogue around water (Lim et al., 2022).

3. Study Area and Methodology

3.1 Study area

The present study focused on the Berrechid plain, a 1 500 km² endorheic basin located south of the city of Casablanca. With low topography, its altitude ranges from 140 m to 450 m a.s.l. It is a semiarid region with a temperate climate influenced by the Atlantic Ocean, which ensures high air humidity. The plain includes an aquifer composed of Pliocene sands, sandstones, and sandy limestones, whose total thickness ranges from 5 to 40 metres. The aquifer is primarily recharged by rainfall, along with runoff water and groundwater inflow from the Settat Plateau (Figure 1). The transmissivity of the aquifer is highly variable, ranging from 10^{-4} to 10^{-1} m²/s, due to the different types of material that comprise the aquifer, and the average storage coefficient is approximately 5% (ABH, 2014). The hydrographic network within the plain is limited to the Mazer, Himer, and Tamedrost wadis, all of which originate from a phosphate plateau and intermittently flow into the Berrechid plain.

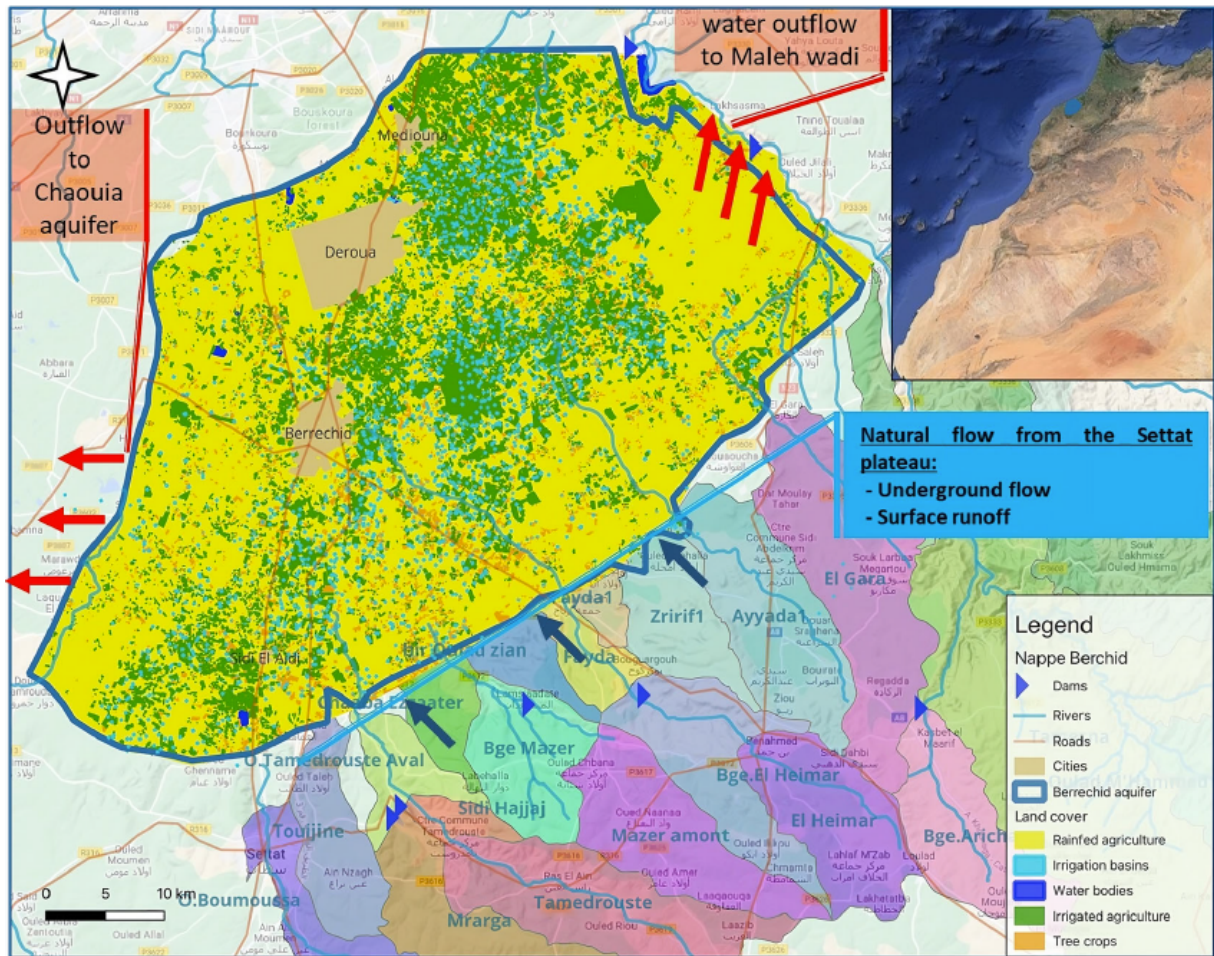


Figure 1. Map of the study area showing the limits of the Berrechid plain, land cover, and the directions of natural inflows and outflows from neighbouring basins.

The study area is made up of nearly 90,000 ha of rainfed agricultural land, 20,000 ha of irrigated land, and 40,000 ha of uncultivated land. The rapid development of intensive irrigated agriculture in the plain, along with subsequent overexploitation of groundwater, can be attributed to easy access to the aquifer, fertile soils, proximity to agricultural markets, and recurring droughts that have negatively affected rain-fed agriculture. This has led to extensive use of private pumps for irrigation and hence to excessive abstraction, resulting in a drop in the water table. In 2018, the Berrechid area contained more than 7,000 wells and boreholes (ABHBC, 2018), further exacerbating the problem.

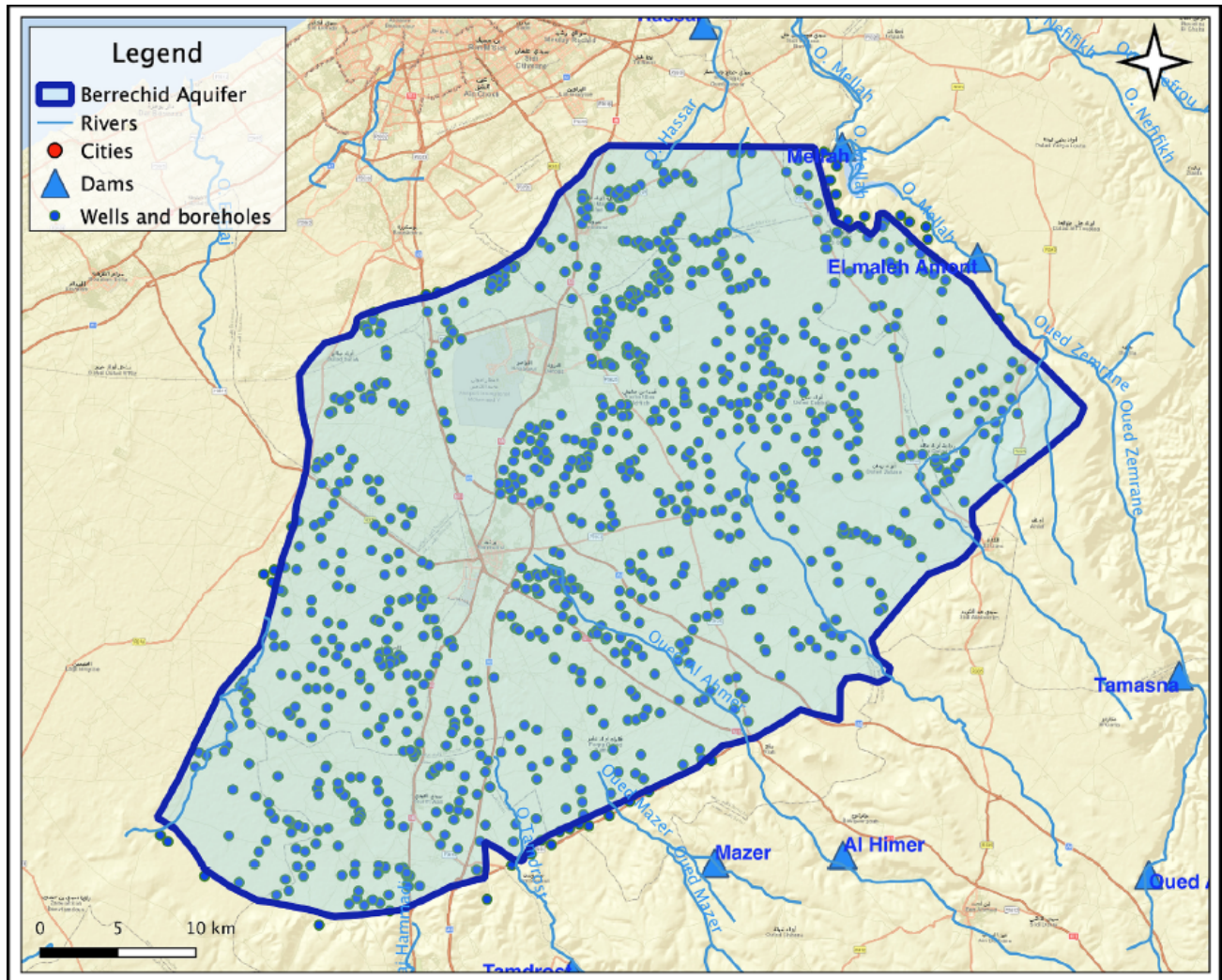


Figure 2: Wells and boreholes in the Berrechid Plain

3.2 Methodology

The methodological approach was inspired by the recent literature on water accounting and builds on the operational FAO water accounting framework (Batchelor et al., 2017). This framework was used to organise and structure the collection, analysis, and presentation of data; it is appropriate for the analysis of water-stressed aquifers such as Berrechid because it makes it possible to investigate the underlying causes of the inability of the aquifer to satisfy water user demand. After defining the spatial limits of the study area, we applied a “follow the water” approach (Kaune et al., 2020) to assess all the water flows entering and leaving the study area to calculate changes in water storage. This included rainwater stored in the soil and evaporation from surface waters. Interactions between the study area and adjacent basins were also taken into account. Figure 3 summarises the steps followed by the study.

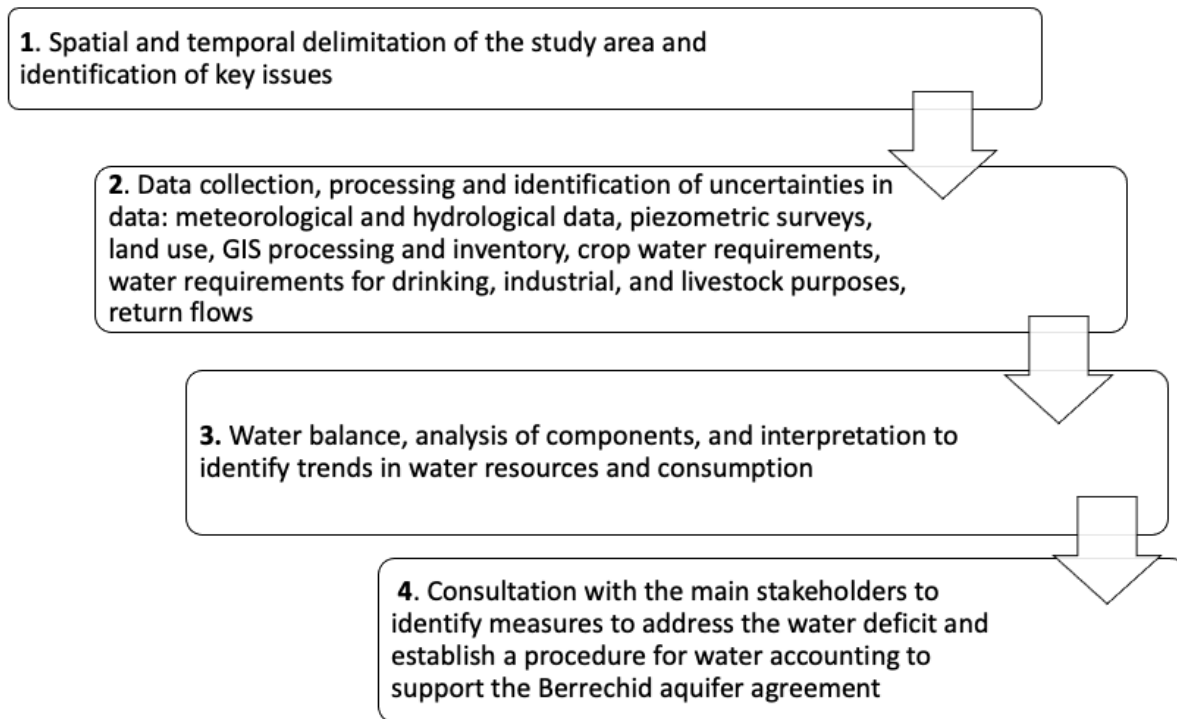


Figure 3: Illustration of the methodology step by step

The process is interactive and iterative, meaning that once the information is provided for negotiations between stakeholders, new scenarios of water supply and (most importantly) water demand can emerge. These scenarios can then be calculated for their effects on the water balance through the water accounting assessment. The water balance includes all sources of water that enter and leave the plain, including rainwater used for agriculture and water imported for domestic use. The aim was to assess water resources and use, with a particular focus on overexploitation of the Berrechid aquifer, the main resource for socioeconomic development of the study area. The importance of rainwater as a potential alternative to irrigation was also evaluated to reduce pressure on the aquifer and limit expansion of irrigated land at the expense of rain-fed land.

Our water accounting exercise included the analysis and interpretation of secondary information from official documents: water resources planning documents, hydrogeological studies and agricultural statistics. The hydrological year (1st of October to 30th of September) was used as the time step for the analysis. The time series examined covered the period 2010 to 2018, for which most of the necessary data, particularly on cropping patterns, were available. The study revealed certain uncertainties in both primary and secondary data, whose accumulation could give rise to controversies concerning the state of water resources. The most significant uncertainty concerned user consumption since there are no water meters on wells and boreholes. Other uncertainties concern flows at the limits of the aquifer and some missing temporal and spatial piezometric data. Two methods can be used to assess quality to ensure the accuracy and reliability of data. The first requires field assessments to check data collected from the flowmeter used in the farmer field school (FFS) and in meetings with the river basin agency

and with staff of the Moroccan office of extension services. The second method is office-based quality control, such as filtering, triangulation, GIS, and trend analysis. An analysis of the water balance and a fractional balance analysis were undertaken to assess the performance of the systems. The equation in our balance sheet combines the principles of IWMI WA (Molden, 1997; Molden & Sakthivadivel, 1999) and the UNESCO Water Accounting Plus framework (Karimi, 2014; Batchelor et al., 2017; Godfrey & Chalmers, 2012). The law of mass conservation requires that, for a given domain and a given period, water inflows are equal to water outflows, plus or minus any change in storage. The water balance equation is thus:

$$P + T_{inflow} = Incremental\ ET + Landscape\ ET + Rainfed\ ET + Q_{outflow} + \Delta S_{GW} + \Delta S_{SW} \quad (1)$$

where:

- P represents precipitation;
- T_{inflow} is inflowing water from other basins (transfers, or for desalination);
- Incremental ET, also called managed water use, refers to water consumed for different uses (irrigation, drinking water, industry, etc.);
- Landscape ET refers to natural evapotranspiration;
- Rainfed ET refers to the evapotranspiration of water that is consumed by crops and other vegetation.
- Qoutflow represents the volume of water leaving the aquifer;
- ΔS_{GW} represents the variation in storage or destocking of groundwater;
- ΔS_{sw} represents the variation in the storage of surface water, which we considered to be zero in our study area.

The quantity of irrigation water required by crops was calculated based on climate data obtained from the INRA agro-meteorological station located in Sidi El Aydi, 20 km south of the city of Berrechid. The equation of irrigation water requirements (IR) is:

$$IR = K_c \cdot K_r \cdot ET_0 - P_e \quad (2)$$

where:

- IR is the irrigation required (mm) for a given crop for a given period;
- P_e is efficient or effective rainfall (rainfall minus drainage and leaching) (mm);
- K_c is the crop coefficient representing the type and development of the crop;
- K_r is the reduction coefficient applied in the case of drip irrigation;

ET_0 (reference evapotranspiration) was calculated based on climate data obtained from the Sidi Aydi INRA agrometeorological station using the Penman–Monteith formula.

Crop coefficients (k_c) were tailored to the specific practices used for the main irrigated crops grown in the Berrechid region, including carrots, potatoes, sweet potatoes, and fodder crops.

Rainfed ET was calculated based on the main rainfed crops grown in the area (wheat, oats, and barley) with average water requirements of 3,000 m³/year. Evaporation from uncultivated land was estimated using a water balance of precipitation and effective rainfall (5% of precipitation) since following the construction of three dams, there was no runoff.

To calculate recharge due to infiltration of rainwater, an infiltration coefficient of 5% was applied to the annual rainfall amount. This coefficient is based on water balance studies using the Turc formula, which is considered to be the most realistic, as it includes a variety of climate parameters. The calculation of the infiltration coefficient was checked using the reference period (2000-2016), average annual rainfall (324 mm), annual Turc formula with an average temperature of 14.5 °C during the rainy season (October to April), and an effective rainfall of 19.5 mm. The river basin agency used a 5% infiltration coefficient based on these calculations (ABHBC, 2014).

The rate of natural flow (runoff infiltration) was estimated to be 6% of the average rainfall according to hydrogeological studies and gauge measurements conducted by the river basin agency (ABHBC, 2014).

4. Results

4.1 A decline in water supply

The water that supplies the Berrechid plain comes from five sources: rainfall, surface water runoff, groundwater, wastewater, and water imported from neighbouring basins. The distribution of rainfall, reconstructed from data recorded at six meteorological stations, is spatially homogeneous due to the region's flat topography.

The average annual precipitation for the 18-year period (2001-2018) was approximately 324 mm, which corresponds to an average annual volume of 486 million cubic meters (Mm³). Historical rainfall data show that over an 18-year period, there is a 50% chance of receiving 300 mm of annual rainfall and an 80% chance of receiving 215 mm of rainfall.

The estimated average annual volume of runoff from the nonperennial wadis that drain the Settat Plateau is 5 Mm³. In 2001 and 2002, flooding affected the city of Berrechid, which prompted the river basin agency to construct three dams on the Tamedrost, Himer, and Mazer wadis to protect the city from flooding.

The aquifer is mainly recharged by rainwater infiltration and inflow of groundwater. Figure 4 **Erreur ! Source du renvoi introuvable.** shows a downwards trend in rainfall recharge and a sharp drop in recharge from the three wadis after the construction of the dams. Climate change, changes in land use, and prolonged drought are expected to have an impact on the relationship between rainfall and runoff, as well as on the balance between surface water and groundwater resources. Additionally, declining or changing rainfall patterns will have an impact on runoff and groundwater resources.

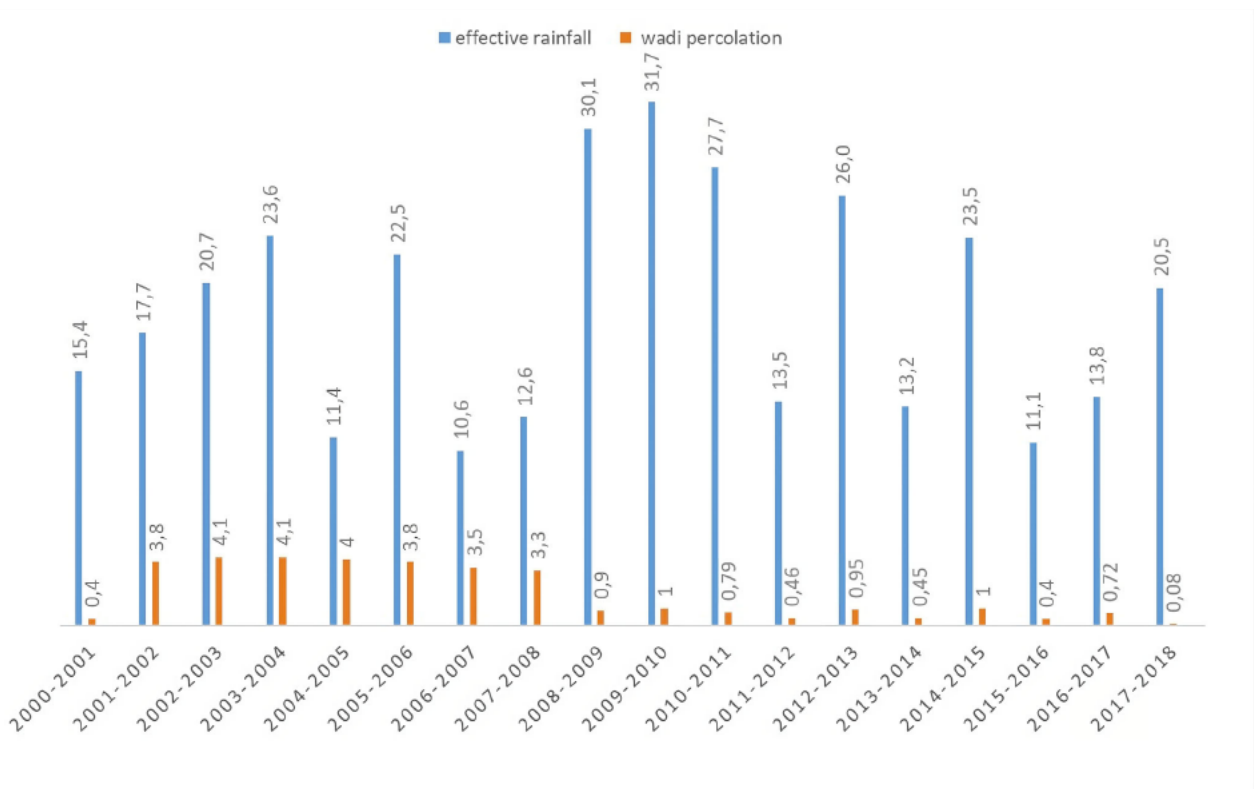


Figure 4: Fluctuations in effective rainfall and runoff infiltration

The average depth of the aquifer ranges from 10 m to more than 120 m and is continually decreasing. The quality of the groundwater is generally poor, with electrical conductivity values as high as 7 mS/cm and chloride and nitrate concentrations exceeding 1.8 g/l and 140 mg/l, respectively³ (ABHCH, 2018).

Unconventional water resources in the Berrechid plain come from six wastewater treatment plants: Settat, Berrechid, Gara, Deroua, Noucer and Mediouna, resulting in a total annual volume of 12.6 Mm³ of treated wastewater. Three wastewater reuse projects are currently underway to expand the use of treated wastewater for agriculture. These projects could reduce withdrawals from the aquifer through the use of treated wastewater from treatment plants, but farmers need to be accompanied to prevent overexploitation of the aquifer when both resources are used. In addition to local water resources, the plain also receives a supplementary supply of domestic water of 6.4 Mm³ imported from the Oum Rbia basin to the south and from the Tamesna dam reservoir to the north.

³ WHO recommends maximum allowable concentration of chloride of 250 mg/l and 50 mg/l for nitrate in drinking water.

4.2 Increased water demand due to the expansion of irrigated agriculture

Irrigation

Irrigated areas increased from 12,700 ha in 2001 when the estimated water demand was 60 Mm³/year to 21,600 ha in 2018 with an estimated water demand of 95 Mm³/year. The increase was particularly sharp after 2009, when subsidies for drip irrigation equipment increased and the cultivation of carrots expanded significantly. Figure 5 illustrates the change in water consumption for the main irrigated crops (carrots, potatoes, onions, and maize grown as a fodder crop) from 2001 to 2018. Carrots and potatoes alone account for approximately two-thirds of the total volume of water used for irrigation (58 Mm³/year).

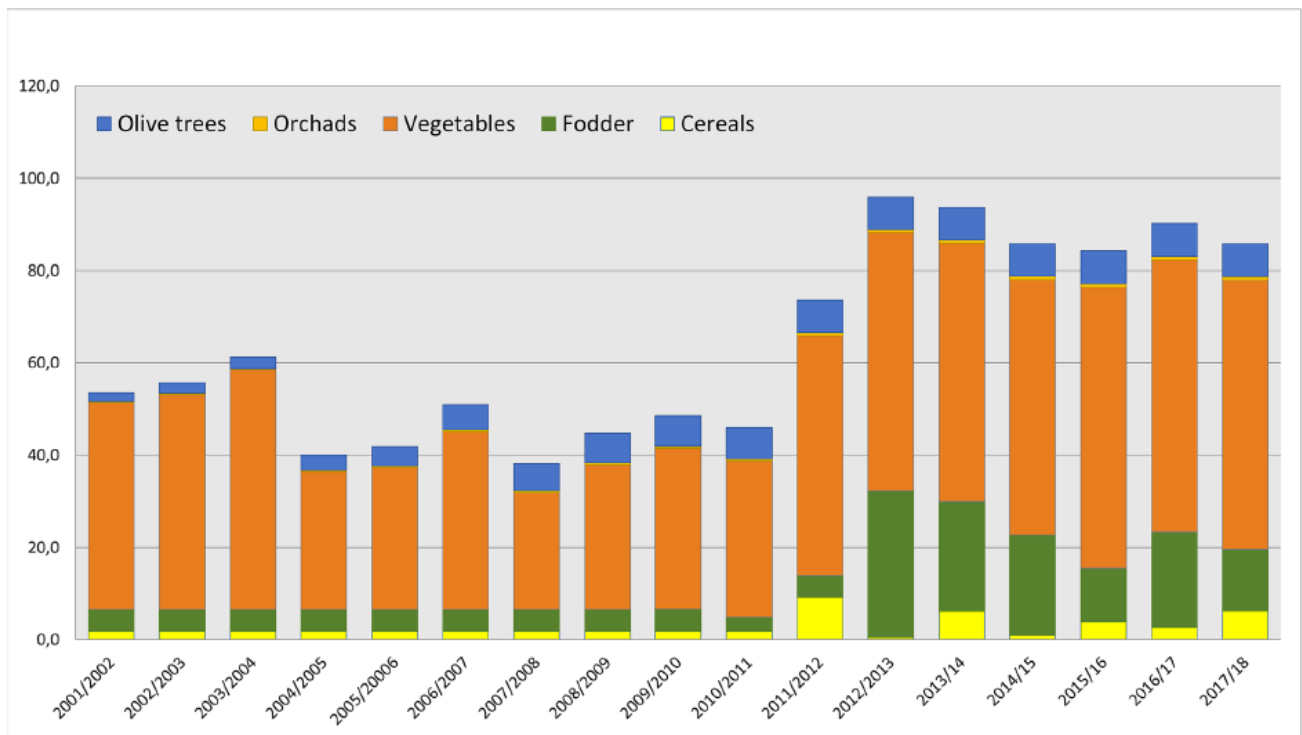


Figure 5: Changes in water consumption by irrigated crops.

The region has undergone a shift in agriculture from the production of rainfed cereals to intensive market gardening. Market garden crops are in high demand in both national markets (e.g., the nearby city of Casablanca) and international markets. This encouraged local large-scale farmers and outside investors to invest in highly intensive irrigated agriculture. In contrast to cereals, which are cultivated in the rainy season (October to April), market garden crops are mainly grown in spring and summer and rely on increased pumping of groundwater. Nearly 70% of water withdrawals occur between April and September (Figure 6).

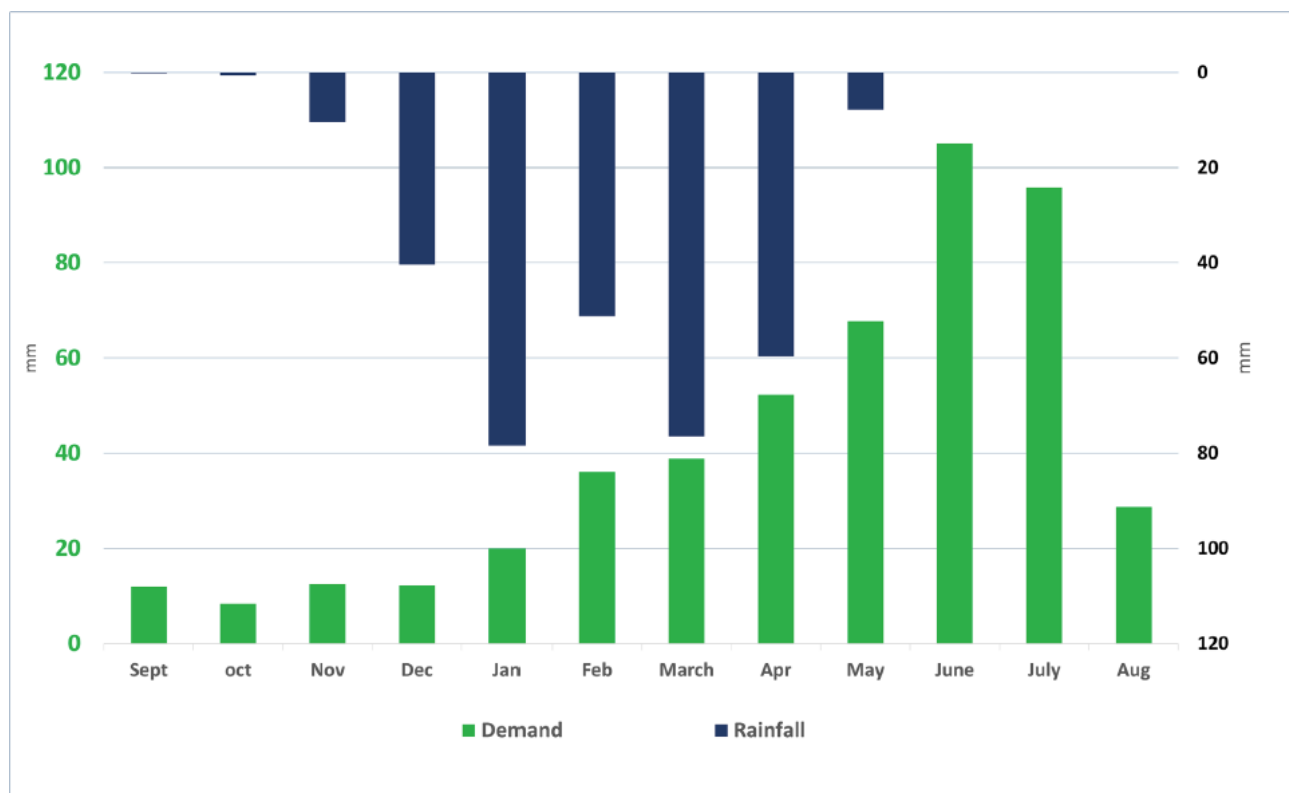


Figure 6: Monthly crop water consumption

As there are no refrigerated storage facilities in the area, farmers store carrots in the field and harvest them up to five months after the crop has matured. In this way, in particular, large-scale farmers ensure a steady supply to the market and obtain better prices. Storage requires an additional 4,000 m³ per hectare between May and September, equivalent to 8 Mm³/year (Table 1).

Table 1: Volume withdrawn for carrots stored in the ground

	May	June	July	Aug.	Sept.	Total area of carrot crop
Harvested area (ha)	1 000	1 000	1 000	1 000	500	4 500
Water consumption (Mm³)	4.5	5.5	6.7	8.6	4.7	30
Consumption in excess of requirements (4 500 m³/ha/year)	-	1.07	2.3	4.2	0.2	7.9

Green water, i.e., water originating from rainfall, is primarily used by rainfed agriculture (90,000 ha) and natural uncultivated land (40,000 ha). An annual average of 430 Mm³ of green water was consumed over the period 2001-2018, with variations depending on local weather and on the extent of irrigated land.

Evaporation occurs from open water bodies, i.e., irrigation basins and wastewater basins. An exhaustive inventory of irrigation basins was carried out using satellite images. Total evaporation from 1,600 water basins was estimated to be 1 Mm³/year. The basins of the six functioning wastewater treatment plants occupied an area of 83 ha, resulting in evaporation of approximately 1.5 Mm³/year.

Most of the water used for domestic (urban and rural) and industrial purposes and for watering livestock was imported from the nearby Oum-er-Rbia basin, (total 9 Mm³/year), of which over 60% is used for domestic purposes in the cities. This was in response to the fact that pumping groundwater in the study area for drinking water by rural inhabitants had been reduced as wells dried up and the quality of the water declined.

4.3 The uncertainties of return flow

The evaluation of return flows refers to the fraction of water that is not consumed and is returned to the system after a cascade of uses. In the Berrechid plain, these flows primarily originate from irrigation return flow, mainly at the field level because the farmers use groundwater pumped from nearby wells. In the present study, we used the theoretical water requirements and efficiency of drip irrigation as the basis for calculation. The rate of aquifer recharge in areas with local and pivot irrigation is a function of the infiltrated volumes resulting from the technical efficiency (90%) of the irrigation system and the uniformity of irrigation (drip line spacing, dripper flow rate) evaluated at 80% (Frenken & Gillet, 2012). In practice, farmers applied significantly larger volumes of water than those used in our calculations (Figure 7; Ouassissou et al., 2019; see also Benouniche et al., 2014). To better reflect actual water use, future water accounting cycles should measure and include actual irrigation efficiencies. The return flow through the infiltration of treated wastewater from lagoons was estimated to be 30% of the volumes of these ponds (ABHBC, 2018).



Figure 7: Overirrigation in a drip irrigation plot - Berrechid plain March 2020

Finally, infiltration during the transport of domestic water, supply, and distribution networks has increased due to the expansion of Berrechid city and rural centres, driven by population growth. This affects soil permeability and reduces groundwater recharge through increased infiltration from this network. Rainwater is more likely to evaporate than to infiltrate, and the increased runoff also generates polluted return flows that require adequate and costly treatment for further reuse. Table 2 summarises the estimation of return flow by components:

Table 2: Return flows

Source of infiltration	Infiltration rate	Average volume of return flow
Wastewater (lagoon basins)	30%	2.7 Mm ³ /yr
Irrigation	- 28% (10% percolation at the head of the network and 18% percolation at field level due to distribution uniformity)	25 Mm ³ /yr
	- Irrigation of carrots stored in the ground	8 Mm ³ /yr
Drinking water networks	5%: 80 km of pipes	1 Mm ³ /yr
	27%: distribution network	

The lack of information on infiltration capacity, groundwater returns, and farming practices adds to the uncertainty surrounding these rates.

4.4 The water balance: continuous depletion of the aquifer

The water balance shows an average inflow of 514 Mm³/year and outflow of 546 Mm³/year (average between 2001 and 2018), as shown in Table 3.

Table 3: Water Balance (average from 2001 to 2018 in millions of m³/year)

Inflows		Outflows			Difference in water storage	
Rainfall	486	Natural outflow		4	Groundwater	-32
Import	6.4	Evapotranspiration	Irrigated agriculture	64		
Inflow of external groundwater	21		Rainfed Agriculture	311		
			Urban	5.61		
			Industry	3.08		
			Natural lands	120		
			Subtotal	504		
		Evaporation of water surface and return flow	of Irrigation basins	0.9		
			WWTP	1.45		
			Return flow	36		
			Subtotal	38		
		Export	-	-		
Total	514	Total		546	Total	-32

The different components of the water balance are represented in the following perceptual diagram (figure 8) of incoming and outgoing flows of the system.

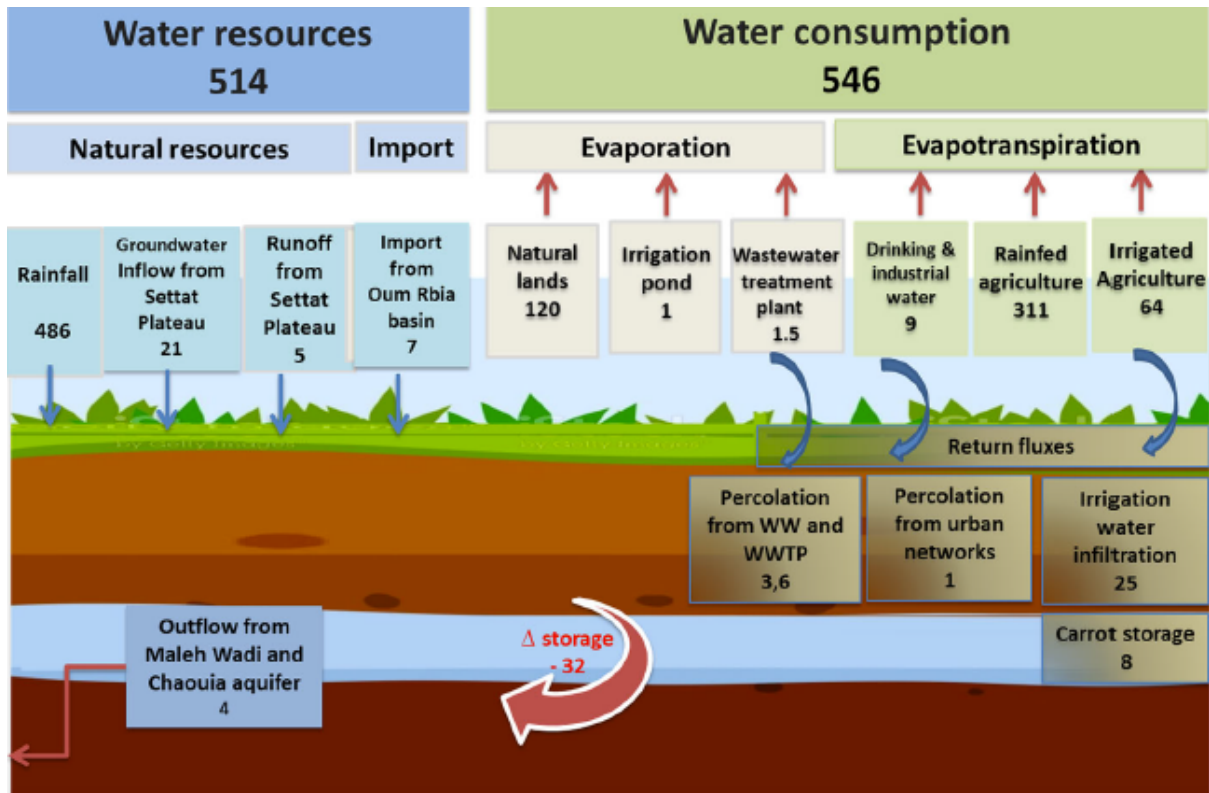


Figure 8: Berrechid perceptual diagram (Average 2001-2018, Mm³/yr)

The change in the piezometric levels between 1980 and 2016 represents a decline of approximately 1 Bm³ over 36 years or an average of 32 Mm³ per year. These figures are comparable with estimates made by the river basin agency, which regularly calculates the water balance, mainly based on groundwater monitoring. For the period from 2008 to 2015, the river basin agency reported an average annual water balance of 36.7 Mm³ (ABHBC, 2018). Out of the stock of 1.5 Bm³ originally estimated in 1980, the currently available stock is less than 500 Mm³. Continuing withdrawal at a rate above the recharge rate will result in the aquifer being depleted by 2035 (Figure 9).

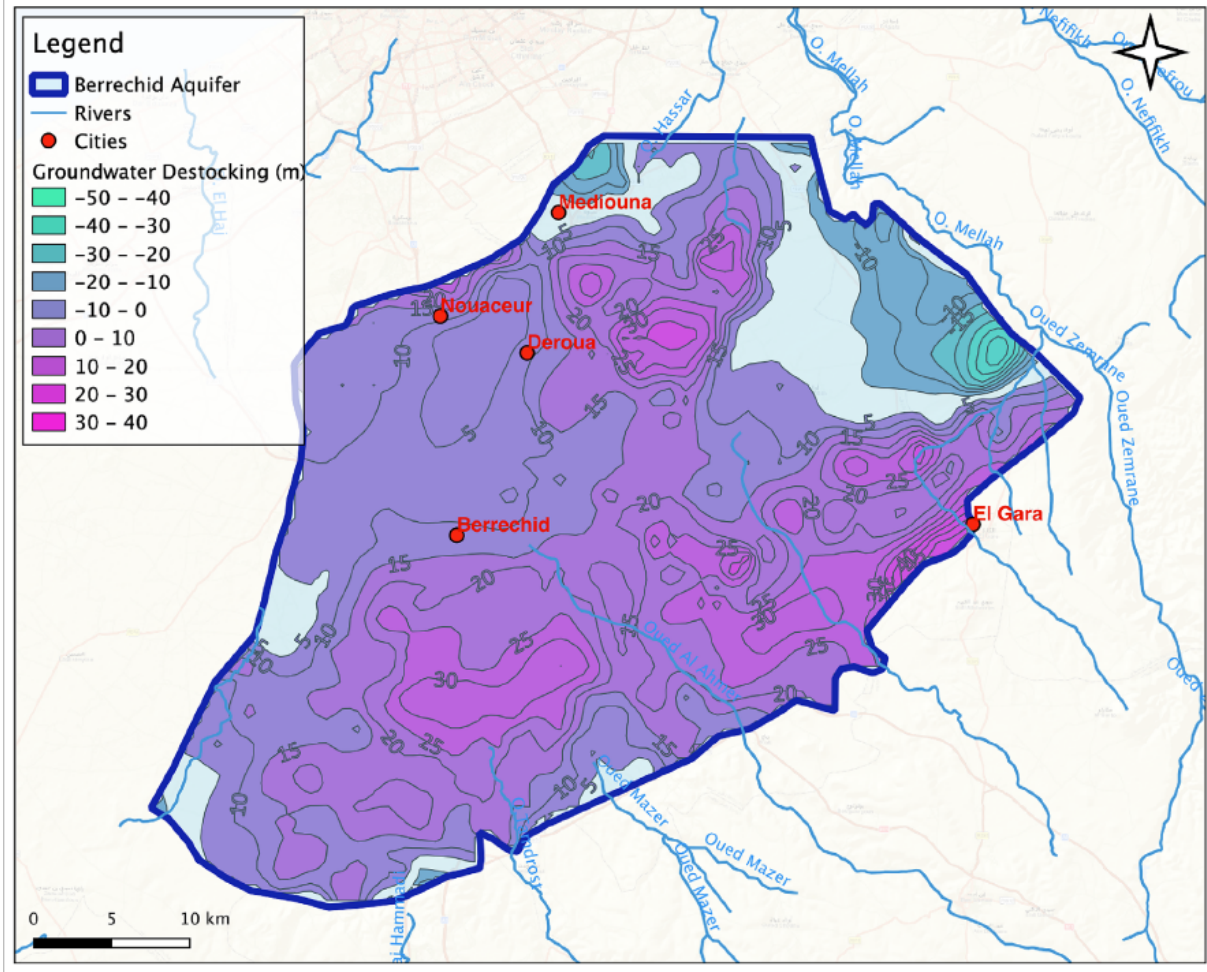


Figure 9: Aquifer destocking (1980-2016)

The total inflow of water (green and blue water) does not meet total withdrawals, resulting in consistent depletion of the nonrenewable stock of water in the aquifer (Figure 10). The current rate of exploitation of groundwater resources is 106%, making the Berrechid aquifer a closed basin (see Molle et al., 2010). The rates of water use in the basin studied here can be compared with other basins in the Mediterranean. For example, the Tensift basin in Morocco has a water use rate of 103% (Tanouti, 2017), and the Macta basin in Algeria has a rate ranging from 119% to 132% (Kherbache et Molle, 2023). The Lower Jordan River basin consumes 121% of its renewable blue resource due to aquifer overexploitation (Venot et al., 2008). These comparisons highlight the challenges faced by stakeholders in many basins in the region in using and managing their water resources sustainably.

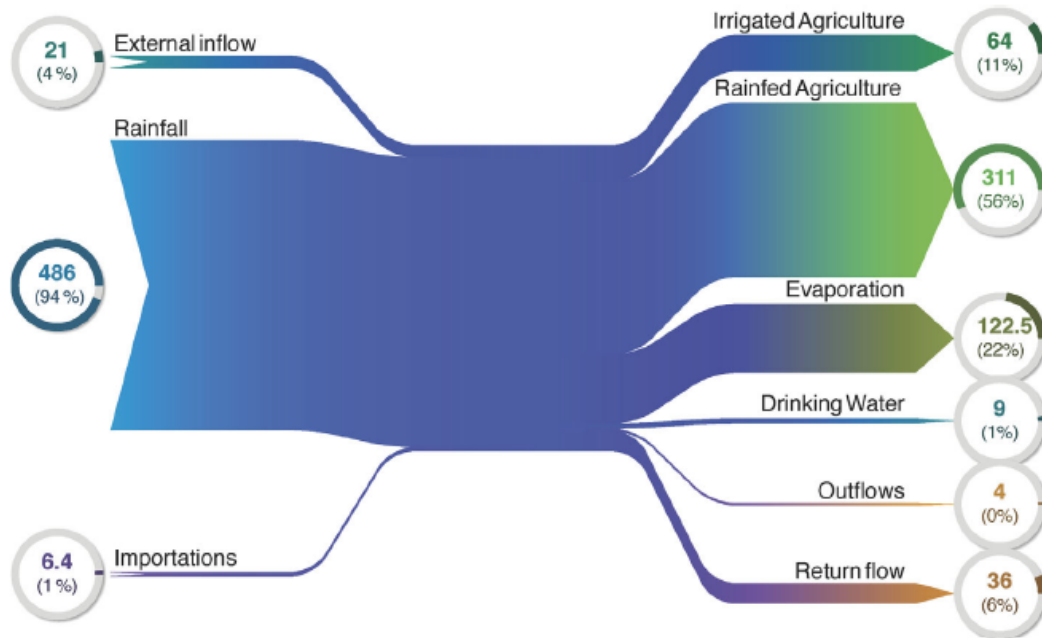


Figure 10: Water balance of the Berrechid plain (average 2001-2018)

Figure 11 shows that there was a shortage of groundwater in six out of the 17 years between 2001 and 2018, as revealed by the calculation of the groundwater balance. This insufficiency has been uninterrupted since 2011. The balance trends indicate a strong correlation between yearly rainfall and fluctuation in the aquifer reserve. On average, the balance sheet is negative at -32 Mm³ per year, with a peak of +209 Mm³/year in 2009-2010 and a low of -192 Mm³ in 2006-2007.

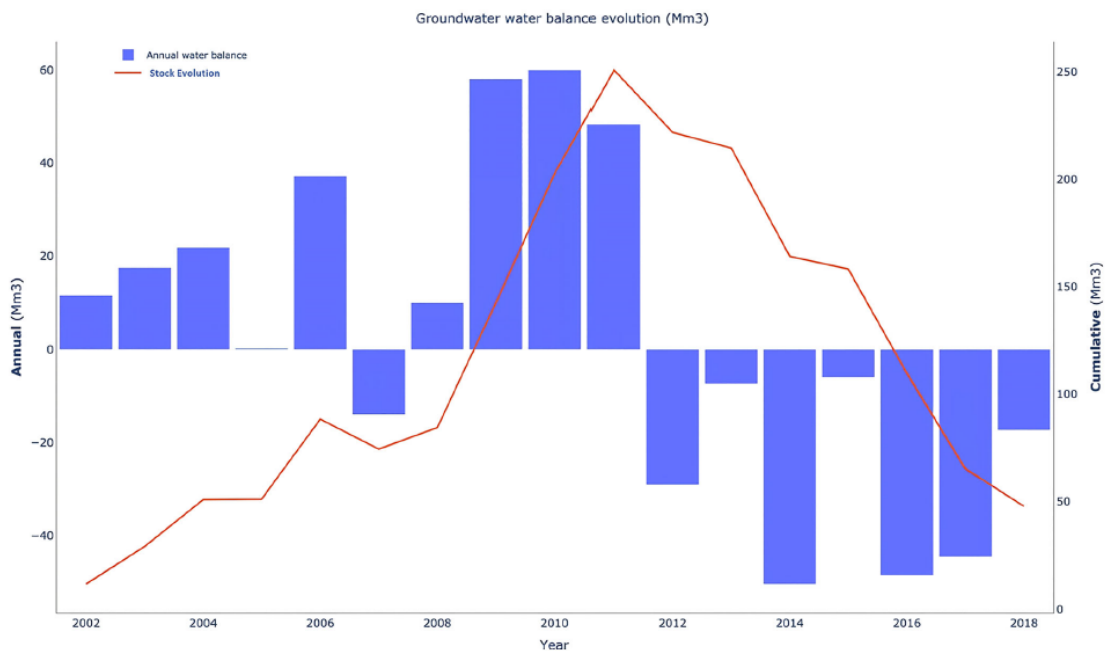


Figure 11: Fluctuations in the water balance of the Berrechid Plain (period: 2001-2018)

Fractional analysis provides a deeper understanding of the importance of return flows and the distinctions in both spatial and temporal terms between water use pathways that are consumptive and nonconsumptive. In this study, the practice of storing carrots in the soil (8 Mm³/year) accounts for almost one-third of the water deficit (32 Mm³/year; Figure 12).

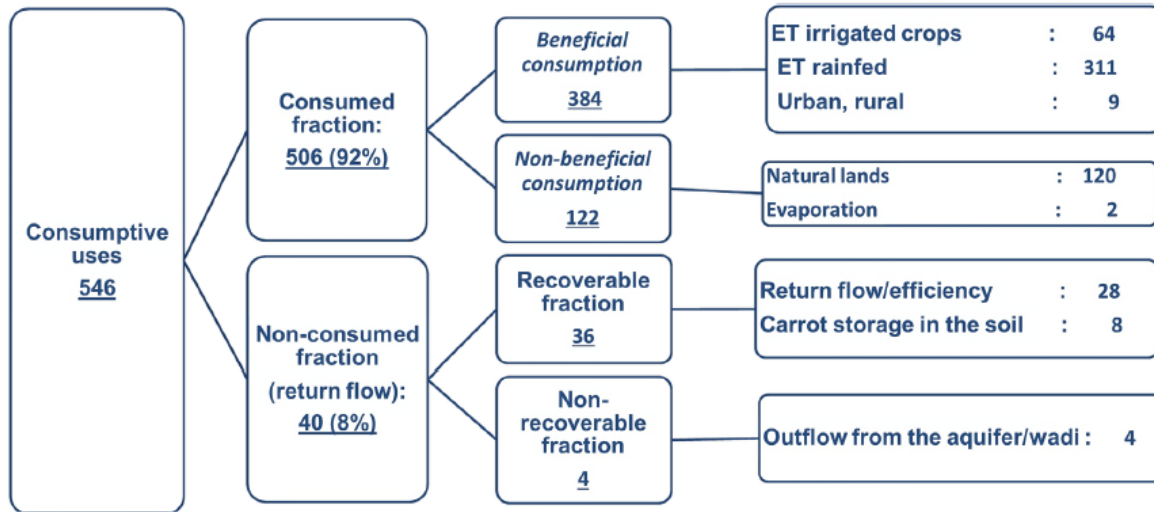


Figure 12: Fractional analysis of volumes in million m³

5. Discussion and conclusion

Typically, there are two possible ways to meet increasing demand for existing water resources: either through the supply side, by meeting demand using new water resources, or through the demand side, by managing consumptive demand to postpone or avoid the need to access new resources (Butler & Memon, 2006). In the water-scarce context of the Berrechid plain, there is only limited scope for increasing water supplies, for example, by increasing recharge through recharge dams, promoting the reuse of treated wastewater, adopting soil conservation techniques to reduce evaporation from natural soils, and promoting rainwater harvesting. Moreover, water basins located nearby, e.g., the Oum-er-Rbia basin, are also under severe water stress. Access to new water resources is therefore limited to importing drinking water from neighbouring basins, which, in turn, would produce some (treated) wastewater that can be reused.

In a water-stressed aquifer such as the Berrechid plain, the main way to address the water imbalance is by reducing water consumption. Several possible ways to reduce water demand have already been tabled by the river basin agency, including improving irrigation practices, improving the efficiency of urban water networks, reducing the irrigated volumes by implementing a quota system through an aquifer contract, promoting the cultivation of less water-intensive crops, encouraging short-cycle market gardening, building a refrigeration unit to store carrots, and creating an inventory of wells to control groundwater use (FAO, 2021). However, while some gains could be made for other water uses

(drinking water, industry), the demand for water for irrigated agriculture will probably have to bear the brunt of water savings. Moreover, the production and export of carrots also involve the export of significant volumes of virtual water, as water-intensive crops contribute to the depletion of local water resources.

Current agricultural strategies promote the cultivation of (rainfed) cereals, possibly with complementary irrigation in drought years. Using green water can help reduce the cost of energy as well as reduce pressure on the aquifer. Improving the water balance would require reducing the demand for water for irrigated agriculture by up to 50% (32 Mm³), probably reducing the surface area by the same amount, which is a major challenge and will not be easily accepted by the different stakeholders. A participatory aquifer management contract is currently used by the river basin agency and its partners, but with little success on the ground, as it is difficult to hold water users accountable (Ouassissou et al., 2019). The intention is to limit irrigation volumes (capped at 5,000 m³/ha/year) through an agreement with farmers. However, such caps are generally impossible to monitor and enforce, and it would certainly be more effective to cap and control the irrigated area per farmer, which would also be easier to enforce (Bossenbroek et al., 2023).

Our results show that conversion to a water-saving system (drip irrigation) since 2008, which was proposed by the river basin agency and agricultural services as the main way of reducing water demand, in fact resulted in an increase in total irrigated area with crop intensification. This fact often surprises policy-makers who subsidise water-saving irrigation technologies, but increased water use after the introduction of drip irrigation has been reported in many countries, including India, Morocco, Spain, and the US (Huffaker & Whittlesey, 2000; Ward & Pulido-Velazquez, 2008; Berbel et al., 2013; Batchelor et al., 2014; Kuper et al., 2017).

Implementing measures to reduce water demand could be accompanied by a shared water accounting system. For example, a web-GIS-based platform could be a participatory monitoring tool used with stakeholders that would enable dynamic calculations of the components of the balance sheet and simulations of various scenarios to support negotiations between different stakeholders on reducing the demand for water. However, such reductions will undoubtedly be fiercely contested by those responsible for current overabstraction. A case study in the study area showed that 80% of the farmers do not access groundwater (or no longer have access to groundwater), while a few large-scale investors cultivate large plots of carrots and potatoes (Ouassissou et al., 2019). This shows that accounting indeed needs to be linked to accountability, whereby all stakeholders are answerable for their actions (Tello & Hazelton, 2018). If this is not the case, the potential of water accounting to improve water governance will remain uncertain.

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