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Research paper

Assessing the sustainability of permitted irrigation from groundwater in the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area in Namibia

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ABSTRACT

The sustainable use of groundwater from karst aquifers is key for sustainable development in the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area (GTO-WCA) in Namibia. The ever-increasing demand for groundwater for irrigation purposes in the GTO-WCA and for argumentation purposes to the Central Area of Namibia has put the aquifer under pressure. Proper groundwater management is therefore required to protect this finite resource. This study assessed the sustainability of groundwater use in the GTO-WCA by assessing the behaviour of groundwater users in the GTO-WCA and by assessing the current legislation and regulatory mechanisms followed by authorities in their allocation of groundwater to the users. The results indicate that groundwater use for irrigation has increased above the sustainable safe yield for the aquifers in this area. The paper elaborates on reasons for the current state of affairs and proposes specific management solutions.

1. Introduction

Namibia is one of the most arid countries in Sub-Saharan Africa. The Cuvelai-Etosha Basin (CEB) in the central parts of northern Namibia in particular, experiences various water-related challenges such as high climate variability, saline groundwater and high population density and growth in urban areas (Liehr et al., 2016). Groundwater is considered to be the most important source of water supply for both agricultural and industrial use in Namibia (Bann and Wood, 2012; Wanke et al., 2008). There is a high demand for freshwater worldwide as a result of population increase, agricultural and economic development (MacKay, 2006). Namibia is no exception, and promoting sustainable use of groundwater resources could limit over-exploitation of this scarce water resource. Sustainable groundwater utilisation is especially important in the Namibian karst aquifers of the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area (GTO-WCA), which is the focus of this article.

Sustainable management should be strongly supported by technical and institutional competency, a legal framework that enables governments to implement sustainable development principles and relevant environmental and socio-economic information (Garduno and Foster, 2010). To safeguard the groundwater use in the country, it is essential to incorporate sound technical information on aquifer characteristics, recharge and safe yields of water supply aquifers so that regulatory institutions can make informed decisions on water restrictions or allocations (Giordano and Villholth, 2007). Where information on these aspects is lacking, it has led to poor management of groundwater resources. In the case of the GTO-WCA, a groundwater study with a groundwater model was done in 2004, which was not validated or updated since. Officials, therefore, manage groundwater according to an outdated groundwater model with obvious data gaps, considering that the data is 15 years old. Also, the 1956 Water Act (RSA, 1956) does not speak to integrated water resources management (IWRM) and is not in line with the current IWRM practices implemented by the Namibian Department of Water Affairs (DWAF). In South Africa, this act has been repealed and replaced with the National Water Act of 1998 (RSA, 1998), which does address IWRM. Ballweber (2006) identified political will, capacitated institutions, and technical cooperation as the three pillars required to support the proper implementation of IWRM. However, in the case of the GTO-WCA, poor political will (to align legislation with current required practices), poorly capacitated institutions (to enact legislation) and the lack of technical cooperation between stakeholders (to identify, integrate and share data and to identify data gaps), all contribute to poor groundwater resources management in the GTO-WCA. Although all the groundwater resource management practices and institutions in the GTO-WCA are not aligned with IWRM yet, we do however observe a transition in water resources management paradigms (van der Voorn and Quist, 2018), from purely technocratic

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water resources management and allocation based on the Water Act (1956), to IWRM, where sustainable adaptive management must be implemented to consider the complex interconnectedness to water resources systems. Water allocation methods differ worldwide, but there is a greater understanding by water resource managers nowadays on the need to manage groundwater resources sustainably (hence the common approach to implement IWRM). Namibia, like any other country that is located in an arid to semi-arid environment, is striving to ensure that its water resources are managed sustainably. However, the failure to implement the policies based on the results of aquifer investigations and the poor enforcement of the aquifer management section of the Water Resources Management Act (WRMA) of 2013 (Namibia, 2013) have caused complacency amongst individual irrigation farmers and the local municipalities about complying with groundwater irrigation permit conditions. All regulations to ensure that the provisions of the WRMA are legally binding have not all been promulgated yet, and the water sector is still regulated partly by the apartheid era Water Act of 1956 (Remmert, 2016). With increasing abstraction for irrigation and the added effect of climate change, groundwater depletion is an unavoidable consequence (Madramootoo, 2012).

In this article, the sustainability of groundwater irrigation allocations in the GTO-WCA is assessed. This water control area consists of two aquifers, the Tsumeb aquifer, and Grootfontein-Otavi aquifer. According to DWA (1990), the Tsumeb aquifer's sustainable yield is estimated at 19 million m3/a, while the Grootfontein-Otavi aquifer's is estimated at 18 million m3/a, with a combined volume of 37 million m3/a. The aquifer allocation plan makes provision for primary use (domestic and stock watering) and industrial use in order of priority. According to DWA (1990), approximately 47% (9.6 million m3/a) of these groundwater resources can be allocated for irrigation in the Tsumeb aquifer and 12% (2.2 million m3/a) for irrigation in the Grootfontein-Otavi aquifer (see Table 1).

A notable decline in the groundwater levels is observed over a 20 year period between 1980 and 2000 over a large area of the GTO-WCA (MAWRD, 2004). Consequently, many springs in the area, including the Otavi fountain east of Otavi, which historically discharged between 100 and 150 m^3/h in the 1980's, have dried up or disappeared (MAWRD, 2004). According to the historical data, the groundwater table in the two aquifers dropped between 1.5 and > 2.0 m/a, totalling an on average drop of 30–40 m over a 20 year period since the 1980's (DWA, 2004). There is, therefore, a need to quantify the magnitude of depletion of groundwater levels in the area to understand the extent of t the aquifer depletion, which is currently poorly documented, as is the case for many developing nations (Konikow and Kendy, 2005).

Globally, sustainable groundwater management has been identified as a long-term priority to manage groundwater resources, as many parts of the world face challenges related to climate change (Gómez et al 2017). Even Namibia will be severely affected by climate change (MET, 2015). Namibia is projected to become hotter in future with a predicted increase in temperature between 1 °C and 3.5 °C and a more variable pattern of rainfall is predicted for Namibia which will cause increased aridity due to the combined effect of variable rainfall and increased evaporation by 2020 (Angula and Kaundjua, 2016). The changing climate is already affecting farming and human wellbeing in parts of Namibia (Angula and Kaundjua, 2016). Namibia has put in place a climate change policy and a supporting institutional framework, but climate change has not yet been integrated into national sectoral policies, such as the water sector (Crawford and Terton, 2016). It is hoped that IWRM under the WRMA of 2013 (Namibia, 2013), linked with water demand management, stricter water resources management and an increased focus on artificial recharge, will assist with the integration of climate change policy in the water sector (Crawford and Terton, 2016). According to the National Planning Commission (2012), Namibia's population is increasing on average over 2% annually. The population increase in local municipalities situated in the Grootfontein-Tsumeb-Otavi Subterranean Water Control area has negative implications for water availability to meet the volumes of water required for domestic and agricultural use. Namibia wants to ensure food security for the country, and therefore needs to ensure groundwater security to sustain agricultural activities.

Table 1
Groundwater use per consumer group for the Tsumeb and Grootfontein-Otavi aquifers.

	Consumer group	Sustainable safe yield per consumer group	
		(Million m^3/ annum)	Percentage
Tsumeb aquifer	Stock-Watering	3	16
	Domestic Use (Municipality of Tsumeb)	3.4	18
	Mining (Industrial)	3	16
	Irrigation	9.6	51
	Total	19	100
Grootfontein-Otavi Aquifer	Stock-Watering	2	11
	Domestic Use (Municipality of Grootfontein & Otavi)	4.8	27
	Mining (Industrial)	9	50
	Irrigation	2.2	12
	Total	18	100

All the irrigation farmers within the Water Control Area (WCA) are required by law to be in possession of a valid permit for the abstraction of water for irrigation purposes. Firstly, a farmer applies for a quantity of water required for irrigation. Then the Geohydrology Division makes an assessment of the quantity that can be allocated in terms of the aquifer management rules for water allocation and makes a decision on the amount to be allowed. Once the permit to abstract has been awarded, the farmer must measure the total amount of water abstracted monthly and submit reports on abstraction rates to the authorities. The measurements can also be read by the control inspectors of the Department of Water Affairs and Forestry (DWAF) during compliance monitoring to ensure farmers are adhering to the permit conditions. According to the annual status report of the Grootfontein-Tsumeb-Otavi Subterranean Water Control area of 2015/16 (MAWF, 2016), the groundwater volumes used for irrigation are higher than the amount permitted by the authorities, meaning that farmers are irrigating more than their permits allow. There is little information on why irrigation farmers are not complying with their permit conditions. Although the study area is considered to have a high groundwater potential, there has been a steady rate of groundwater depletion according to the groundwater levels recorded in the area (MAWF, 2016). This research, therefore, assesses the sustainability of aquifer management practices and reviews whether recommended quotas for irrigation by the DWAF are considered to be in line with the goal of achieving sustainable groundwater utilisation of the two aquifers by the agricultural sector. By gauging the perceptions of farmers in the study area on current and potential water utilisation, this study will contribute useful information on groundwater availability and sustainable groundwater use in the area.

2. Background on water governance for Grootfontein-Tsumeb-Otavi Subterranean Water Control Area

The GTO-WCA was proclaimed as a Water Control Area on November 13, 1970 in terms of section 28 of the Water Act No54 of 1956 (Heyns, 2005). The control and use of subterranean water in a proclaimed water control area are stated in the Regulations No. R. 1278 dated July 12, 1971 (DWA, 1971), requiring that groundwater use in the area must be permitted by the Minister of Water Affairs and Forestry. No permit is required for the abstraction of water for domestic purposes, which in terms of the Regulations includes the "use for sanitary purposes, the watering, and dipping of stock and the irrigation of crops on an area of land not exceeding 1 ha". In 1969 the South West Africa Affairs Act was promulgated in South Africa to control the territory of

Namibia and provide funding for development plans (Heyns, 2005). This meant that most of the legislation in South Africa became applicable to Namibia, including some clauses in the South African Water Act no. 54 of 1956 (RSA, 1956; DWA, 1956). As already mentioned, this act is no longer in use in South Africa and has been replaced with the National Water Act of 1998 (RSA, 1998), which considers aspects such as IWRM, which the 1956 Water Act does not. Some regulations under the WRMA of 2013 (Namibia, 2013) must also be promulgated to ensure that provisions under the WRMA are legally binding. Although the Regulations No. R. 1278 dated July 12, 1971 (DWA, 1971) is still being used as an instrument to manage, control and protect the groundwater resources, lack of proper enforcement from authorities to ensure compliance by the users and promote sustainable management of the water resources is hampering the process. Section 170 of the Water Act (Act 54 of 1956) deals with offences and penalties, but the regulations under R1278 did not adequately provide the details for the enforcement of the permit system to ensure compliance with the permit system. The recourse in a situation like this is to amend the regulations, but in the absence of any amendments, it is important make the groundwater users aware that if they comply with the permit system, they would protect the resources they rely upon. If all users cooperate, the sustainable use of water can be achieved without conflict and the imposition of penalties.

Managing a karst aquifer is usually challenging because of its geological complexity (León and Parise, 2009). However, the management of the GTO-WCA karst aquifers is further complicated by the lack of integrated development planning, legislation that does not address IWRM adequately and poor implementation of legislation. A steady increase in agricultural activities may lead to groundwater depletion in these karst aquifers (Taheri et al., 2016). Over-exploitation of the karst aquifers could result in the formation of sinkholes. Although there is an acknowledgement of existing sinkholes in the area, limited studies investigate the link between human activities and sinkhole formation in the GTO-WCA. Managing the groundwater resources in the GTO-WCA proved difficult without the involvement of the local stakeholders. Therefore, to ensure proper management, allocation, and monitoring of the two aquifers in this WCA, the Namibian government encouraged the formation of a local structure by the local stakeholders for joint management of the groundwater resources (Heyns, 2008). Stakeholders supported joint management of the aquifers and this led to the establishment of the Karst Water Management Body (KWMB) in accordance with the National Water Policy (MAWRD, 2000) and the Water Resources Management Act no 24 of 2004 (MAWRD, 2004), which was never enforced and is now replaced by the Water Resource Management Act no 11 of 2013 (MAWF, 2013). The Namibian government endorsed and recognised the establishment of the KWMB as representative of the GTO-WCA groundwater management body. Under the constitution of the Karst Water Management Body it stated that its objectives are "to optimize the management and achieve the most beneficial, sustainable use of the water resources of the Water Control Area". The partnership was viewed as the best way to achieve maximum security in the supply of water to all people in the WCA and to ensure transparency in the allocation of water quotas to different users. All new permit applications or renewals that were submitted to the DWAF for abstraction of groundwater were scrutinised based on the Water Act No 54 of 1956 and recommendations of 10,000 m^3/ha/a across all crop types, as an approach to managing the groundwater sustainably (MAWRD, 2004). All the water permit applications submitted to the DWAF for processing were referred to the KWMB for their input before the application was finalised. These provided the KWMB the power to examine the recommendations from the DWAF and to make additional recommendations based on the prevailing situation on the ground.

Although the KWMB did not have the authority to make a final decision, their inputs were effective, especially on an advisory level to the DWAF regarding illegal irrigation in the GTO-WCA. Although some water permits were suspended or rejected by both the DWAF and the KWMB, irrigation farmers continued to abstract groundwater and no punishments were handed out to those not complying. After the formation of the Basin Management Committees (BMCs) according to the new Water Resources Management Act No 11 of 2013 (MAWF, 2013), the BMCs replaced the KWMB according to the IWRM concept. Although BMCs have been established in some parts of the country, the new act awaits its commencement. The new Water Act recommends the establishment of BMCs under section 20 of the Water Resources Management Act, No. 11 of 2013 (MAWF, 2013). Whether the establishment of BMCs will improve the sustainable management of groundwater in the GTO-WCA compared to the KWMB, is still to be determined. The implementation of a basin management policy based on river catchments only, without taking cognisance of the fact that aquifers can lie across catchment boundaries. This is a major failure of basic comprehension on the part of the DWA, and the DWA needs to adapt this weak policy to address specific geohydrological environments and to be more practical and scientifically accurate.

After the adoption of IWRM in Namibia, Basin Management Committees (BMCs) were formed around the country with the sole purpose to manage water resources in a holistic approach. However, because the Basin Management Committee (BMC) establishment was based on surface water catchment areas, it has split the GTO-WCA aquifers between three BMCs - the Cuvelai-Etosha, Okavango-Omatako and the Ugab-Huab Basin Management Committee (Namibia, 2010). Consequently, stakeholders in this WCA that were part of Karst Water Management Body are now divided among these three BMCs. Currently, the majority of the stakeholders (especially the irrigation farmers) do not participate in the quarterly BMC meetings, as they regard some BMC meetings to be concentrating only on surface water (especially meetings for the Okavango-Omatako Basin Management Committee). Previously, meetings were organised by the Karst Water Management Body and the DWAF was invited to give updates on the groundwater status of the GTO-WCA. During this time, concerns were raised by both parties about sustainable groundwater management in the GTO-WCA. However, BMCs are currently not involved in the issuing of abstraction permits, and this raises a question amongst stakeholders about their role and responsibilities and how they can influence groundwater management in their respective areas. Although the BMC has been formed in the area, there is no existing law in place that authorise the formation of the BMC. The Water Resources Management Act. No. 11 of 2013 is not enforced yet, therefore the Department is still using the Water Act of 1956, which does not provide for the formation of BMCs.

3. Study area

The study was conducted in the GTO-WCA, covering an area of approximately 25,500 km^2, including the Otavi Mountainland with its Kalahari foreland. The GTO-WCA, located in the central part of northern Namibia (Fig. 1), is a significant food production area for Namibia in terms of livestock and crop farming. Due to the presence of the karst aquifers in this area, it is considered an area of high groundwater potential (Christelis et al., 2001). The carbonate rocks found in the karst, host large volumes of groundwater resources of good quality and it is of national interest to utilize this groundwater in a sustainable way. The large groundwater supply potential of the karst aquifers can be explained by the comparatively high rainfall in this specific area ($\pm$500 mm) (DWA, 2004) linked with the good groundwater storage potential in the karst aquifers. The thin soil cover and the high porosity and permeability of the dolomite and limestone, which is a result of intense fracturing of the host rock due to chemical weathering, facilitates rapid infiltration of rainfall and storage as groundwater. The GTO-WCA (also known as the Maize Triangle) has three local municipalities (Tsumeb, Grootfontein, and Otavi) and is dominated by irrigation and livestock farming.

The occurrence of the Nosib Group sediments and the virtually impervious basement rocks along the E-W trending Nosib Anticline created a hydraulic barrier in N–S direction that separates the Karst

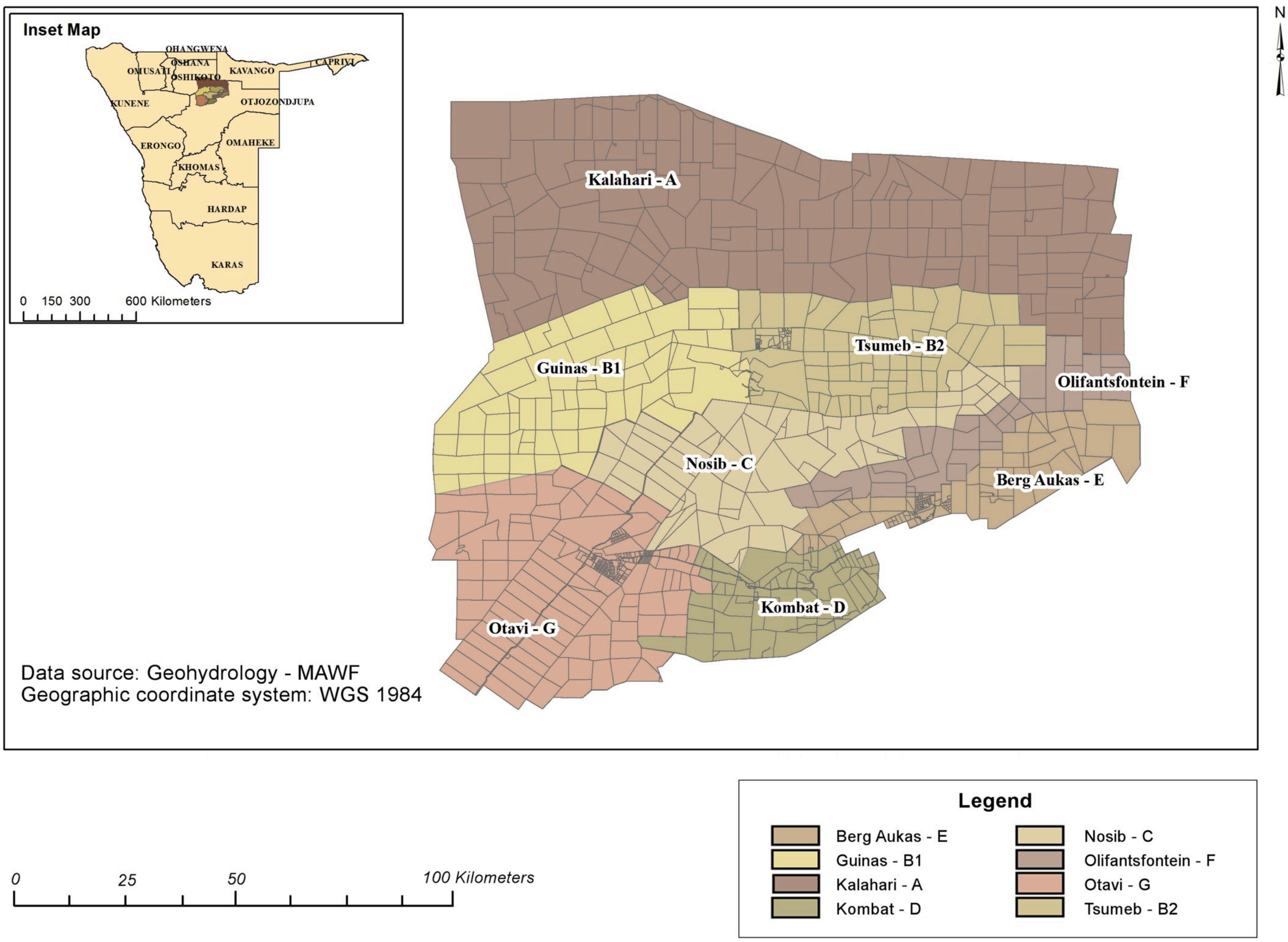

Fig. 1. The Grootfontein-Tsumeb-Otavi subterranean water control area (DWA, 1990).

aquifers into a northern portion, the so-called Tsumeb Aquifers, and a southern portion, the Grootfontein-Otavi Aquifers. These aquifers are divided into eight sub-regions (Fig. 1) and each sub-region has its recommended environmental sustainable safe yield for irrigation purposes for the specific sub-region (DWA, 1990). The GTO-WCA consists of two aquifers, the Tsumeb aquifer (IV) and Grootfontein-Otavi aquifer (I to III), see Fig. 2.

4. Methodology

Data collection to assess the sustainability of aquifer management practices and to review the irrigation quotas was done by means of both qualitative and quantitative methods. A semi-structured questionnaire was designed to capture the required information. The questionnaire entailed mostly closed and a few open-ended questions on the respondent's background, their knowledge and perspective on recommended water irrigation quotas, the suitability of groundwater use, the identification of alternative groundwater uses, their experience with suggested quotas, questions on contributing factors to non-compliance with permit conditions and lastly, questions on economic losses and benefits based on recommended water usage. The survey targeted specifically irrigation farmers in the area, as they are the majority water user in the area and have a high influence on aquifer sustainability. Although the evaluation of sustainability was cross-cutting element, there were specific questions assessing the willingness and ability of the farming community to comply with the irrigation quotas. Open-ended questions (such as questions asking about alternatives to irrigation farming) were thematically coded to identify the most common themes emerging from the open-ended answers of the respondents. The closed questions were already categorised according to information derived during water resources management of the GTO-GWA (i.e. registration information of boreholes, reported irrigation volumes, reported monitoring of water levels). The codes for the closed answers were therefore assigned according to the pre-determined categories.

The study area is divided into eight sub-regions as shown in Table 2, although sub-region E and F are managed as one unit, therefore the total managed sub-regions are seven. Each sub-region has a specific volume permitted for groundwater abstractions. Sixty farms were randomly selected over the study area. Because some respondents owned multiple irrigation permits (up to 4 per farmer), the targeted respondents who were interviewed were reduced to a total of 37 during the survey.

The survey was conducted by two interviewers. English questions were translated into the Afrikaans language in the case where Afrikaans-speaking respondents were not fluent in English. Some information on actual groundwater usage in the area was collected via a literature review of DWAF documents. Qualitative information was collected from stakeholders such as individual experts, irrigation farmers, DWAF personnel that have experience working in the area, organizations associated with crop production and directorates within ministries mandated to support farmers with crop production and water supply. The data were analysed using the IBM Statistics Package for Social Sciences (SPSS), version 22, and the questions were categorised and coded in order to transform the data into table and graphical format.

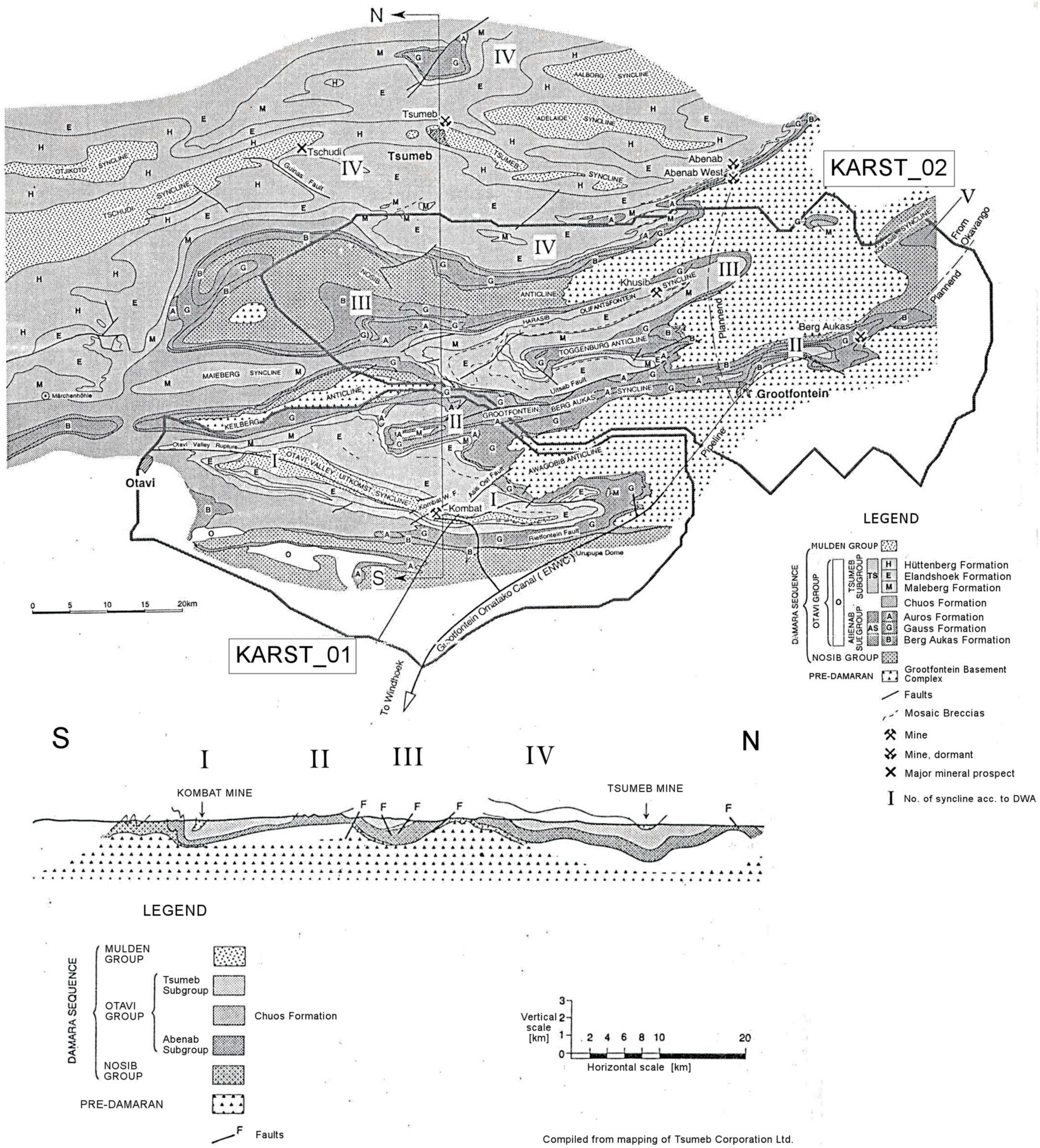

Fig. 2. Geological map of the Tsumeb aquifer and Grootfontein-Otavi aquifer (after BGR, 1997).

5. Results and discussion

A total of 37 respondents in the GTO-WCA were interviewed. The majority of the irrigation farms (56.8%) are managed by landowners, followed by farm managers at 32.4% and the remaining farms are managed by Chief Executive Officers. Decisions on water use on the farms are largely taken by farm owners that have experience and knowledge about their farming environment and should play a role in the sustainability of groundwater use in the area. Of the 37 respondents, only 3 farmers were from the previously disadvantaged group.

5.1. Sustainable groundwater use

Namibia is one of the driest countries in the world and about 48%of the water in the country is used for irrigation. Water demands for agricultural purposes have increased steadily over the years (Dalin and

Table 2
Respondents surveyed in each sub-region of the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area.

Sub Area (Irrigation permit holders only)	A	B1	B2	C	D	E&F	G	Total
Sustainable abstraction allowed (million m^3/a)	0,5	2.4	6,2	0,5	0,2	0,5	1,5	11.8
Total irrigation permit holders	11	10	63	6	8	9	22	129
Total irrigation permit holders surveyed	3	5	15	2	4	2	6	37
Percentage of irrigation permit holders surveyed in each Sub-area	27	50	23	67	50	22	27	29

Conway, 2016). The situation is exacerbated by frequent droughts in the GTO-WCA, with climate predictions indicating that Namibia will become drier and rainfall more variable, meaning that droughts and floods are likely to become more frequent and intense (Turpie et al., 2010). The erratic weather conditions and recurring droughts in Namibia have resulted in significant drawdowns of shallow and deeper groundwater by irrigation farmers to meet their crop water requirements and by local municipalities to supply water for domestic purposes (Dalin and Conway, 2016). Groundwater is seen as a crucial source of water supply for irrigation in the arid and semi-arid areas (Madramootoo, 2012). Data from the Namibian Department of Water Affairs indicate that current groundwater use is above the sustainable yield of the two aquifers (see Fig. 3). As per permit conditions, farmers are required to monitor groundwater levels in their respective farms to understand groundwater fluctuations in the area, and this monitoring must occur on a continuous basis. However, 27% of the respondents do not measure rest water levels on their farms. Even though this is the function and responsibility of the water resource managers, if water users engage in monitoring of rest water levels on their farms, they would better understand the impact of the land use activities on the groundwater resources.

According to DWA (1990), the sub-regions in the two aquifers were each allocated a certain portion of the available sustainable yield of the aquifers for irrigation (see Table 3).

These water volumes were divided among the irrigation farmers in the sub-regions. The criteria for allocating abstraction quotas was that the application under consideration can only be considered if the allocation quota has not been reached (Heyns, 2008). All the abstraction

Table 3
Sub-region sustainable yields of the Tsumeb and Grootfontein-Otavi aquifers.

	Sub-region	Sustainable safe yield per sub region (m^3)
Tsumeb aquifer	A	500,000
	B1	2,400,000
	B2	6,200,00
	C	500,000
	Total	*9,600,000*
Grootfontein-Otavi Aquifer	D	200,000
	E + F	500,000
	G	1,500,000
	Total	*2,200,000*

permits awarded in the area should be below 10,000 m^3/ha/a for each crop type. Nonetheless, DWAF has in recent years increased the groundwater allocation to the irrigation farmers' way above the recommended sustainable yield for each sub-region, as shown in Fig. 3. Groundwater allocation above the sustainable yield can be used to gather more information about the aquifer behaviour under different operational conditions, but such decisions must be accompanied by rigorous monitoring, especially in the case of sub-region B2 that has high water use.

According to the resource managers at DWAF, an irrigation quota of 200,000 m^3/a, requires an Environmental Impact Assessment (EIA) before approval is granted. Irrigation farmers who were able to conduct an EIA to prove that an increase to their allocated quota above the 10,000 m^3/ha/a, would not have a negative impact on the groundwater, were awarded an additional increment. However, this is against the recommendation from the unpublished policy "Revised criteria to be considered when allocating a permit for the abstraction of groundwater for irrigation purposes in the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area" (DWA, 2004) which advocates the sustainable utilisation of groundwater by recommending 10,000 m^3/ha/a across all crop types, instead of promoting exploitation through groundwater quota increases by individual farmers with the financial means to afford an EIA. Furthermore, the groundwater model that was developed in the 1990's to determine the sustainable groundwater yield in the area (DWA, 1990) has never been updated to consider new changes such as population growth, increased water use in the industrial and irrigation sectors, the effect of climate change on groundwater recharge over the last three decades or the behaviour of the aquifers under different operational conditions.

All irrigation farmers in the WCA are legally required to submit their

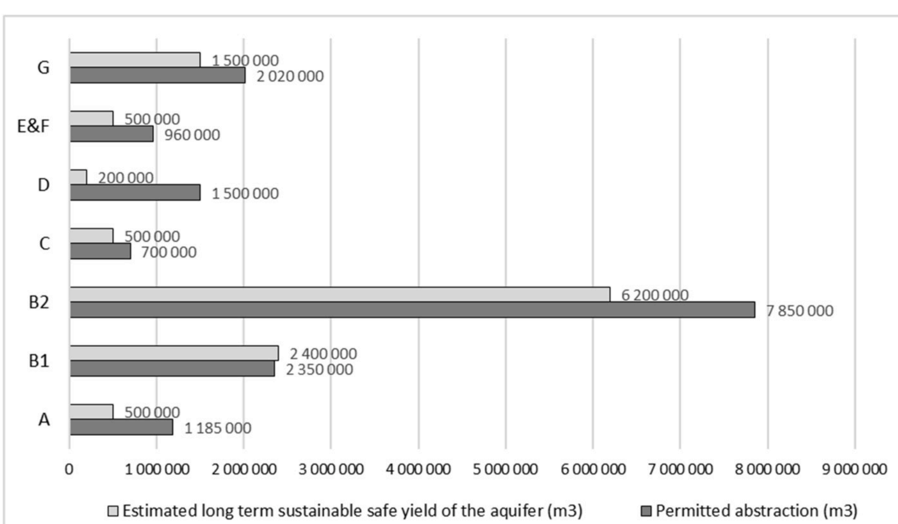

Fig. 3. Total sustainable safe yield for irrigation against the total volume allocated for irrigation by DWAF in each sub-region.

abstraction rates to the DWAF on a quarterly basis. About 19% of the survey respondents indicated that they do not submit their abstraction returns. These abstraction returns represent the total amount of groundwater abstracted per annum by the farmers for irrigation purposes. Because not all farmers are complying with submitting their annual abstraction returns to the water resource managers, there is a misrepresentation of the total volume of groundwater used by irrigation farmers on an annual basis. Groundwater abstraction for irrigation has risen significantly in almost all the sub-regions of the GTO-WCA over the last few years, as indicated in Fig. 4. According to the respondents, groundwater is the only source of water supply for agricultural activities in the GTO-WCA as rainfall is too erratic to be considered as a source of water for irrigation, although in good rainfall seasons, less groundwater is used for irrigation. The majority of irrigation farmers irrigated more than their allocated quotas during the period from 2013 to 2016. During this period, the area experienced frequent droughts and high temperatures and no measures were put in place to ensure a reduction in groundwater abstraction. Even though the permit conditions stipulated that in cases where the groundwater levels approach critical levels that the allocated permit quotas may be reduced or suspended (MAWRD, 2004), no such reductions or suspensions were ever implemented or enforced by DWAF. Most irrigation farmers, therefore, increased their groundwater abstraction as a way to counter the high temperatures, to keep their crops alive during times when the temperatures were too high. If there is a rainfall "drought" during the growing season, farmers would likely pump more water to save the crops and make profit to enable the farmer to repay the capital and interest on his irrigation project. Although this is an unsustainable activity relative to the safe yield of the aquifer, the aquifer can possibly recover, while a crop is unrecoverable if they die from lack of water. However, the measure in which the aquifer recovers and the economics of operating the aquifer on an optimal basis can only be determined by proper and effective monitoring of the aquifer.

Some farmers are addressing bush encroachment on their farms as part of measures to increase aquifer recharge by removing alien vegetation which uses large volumes of water and reduces recharge. The recharge will, therefore, improve over time and the yield of the aquifers can be adjusted upwards. However, some of those farmers indicated the need to increase irrigation quotas above their current allocated quota as a way of rewarding their efforts of bush encroachment management since reduction of bush encroachment is not subsidized by the state and the farmer must recover the cost from increased agricultural production over the short term. This means that water that might be saved after bush encroachment management can still be lost through increased groundwater abstraction. Many farmers do not really support water-saving practices, as their main goal is to ensure a good harvest and to recover the costs of their investments in infrastructure and crops (seed, plough, plant, irrigate, pest control, harvesting, transport, etc). Some individual farmers believe that drilling deeper boreholes to tap into a deeper aquifer is a sustainable option to ensure pumping is not affected by drawdown and to ensure continuous groundwater supply for irrigation. None of the respondents are willing to reduce their cultivation size in times of drought as a way to save the aquifer. The fact that the Water Act (1956), which does not focus on sustainability, is still used to manage water resources in the GTO-WCA, and the fact that most farmers come from a regime where water was viewed as private water, may account for this unwillingness.

Sub-region B2 has a total of 6,2 million m^3/a as a sustainable safe yield for the area, however, the currently permitted allocation of approximately 10,5 million m^3/a, is above the sustainable yield (see Fig. 4). This sub-region has the highest water use for irrigation and the groundwater abstraction is rising on an annual basis.

5.2. Compliance with groundwater abstraction permits

Groundwater use in the WCA is regulated by the Water Act, (No 54 of 1956) under sections 29(a) and 29(b) and requires a permit for drilling and constructing a borehole in a WCA (DWA, 1956). Upon completion of drilling the borehole, another permit is required for the abstraction of groundwater, which might be subjected to different conditions such as the total amount to be abstracted (Theesfeld, 2010). In this area, where enforcement of legislation is lacking, there is high level of non-compliance with the permit conditions, as indicated by our survey that shows that about 76% of respondents do not comply with their permit conditions. Seventy percent of the respondents indicated that their allocated quotas were not sufficient to fulfil their crop production

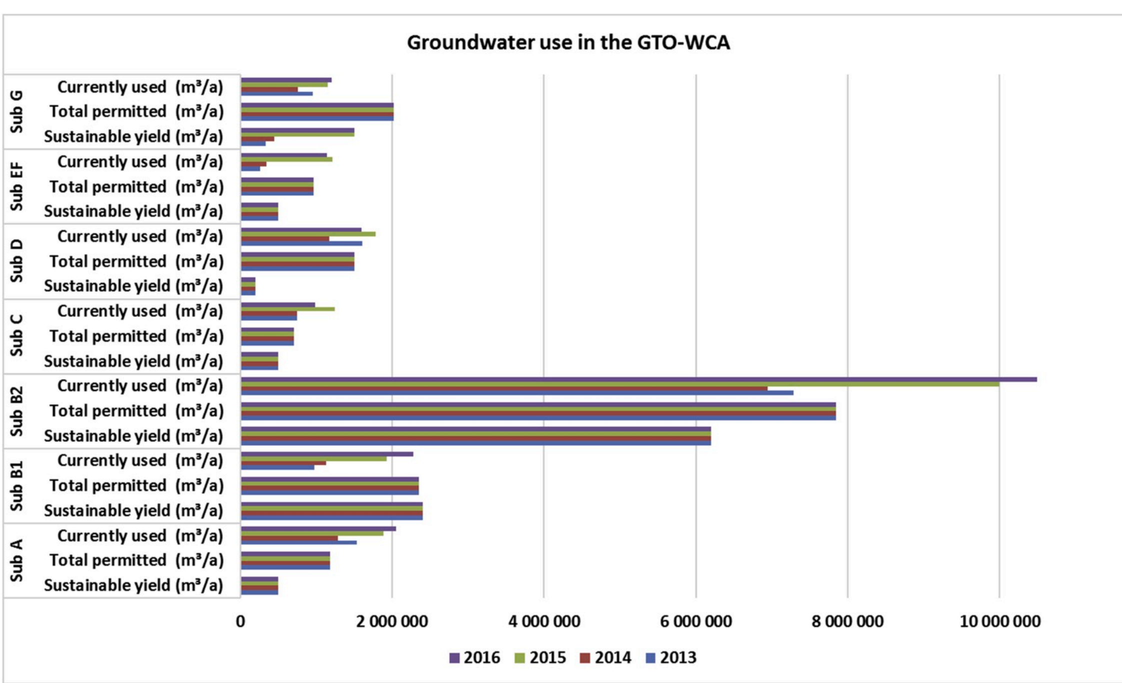

Fig. 4. Groundwater use for irrigation purposes in the study area (Data source: DWAF).

requirement. Climate change is affecting agricultural activities and the farmers need to abstract more water to save the crops and ensure not losing on investments. Therefore, abstracting more groundwater than their allocated quota will enable them to meet their irrigation needs. With high investments in the irrigation sector, many farmers are unwilling to compromise on their investment by reducing production.

Climate change threatens the livelihood of many Namibians with high temperatures affecting crop harvests, especially in the communal areas (Turpie et al., 2010). During the survey, frequent dry spells and high temperatures were identified as contributing factors to many farmers irrigating their crops more often in an effort to save the crops from heat. Irrigation farmers claimed that during high temperatures, crop growth can be affected which can also affect production, therefore irrigating more often is seen as a solution. Higher irrigation levels usually occur during the day when the temperature is at its highest. Eighty-six percent of the respondents use centre pivot as an irrigation method (Fig. 5). Respondents view centre pivot irrigation as consuming less water than the flood irrigation method and view it as the most suitable irrigation method for maize cultivation. However, if farmers irrigated at night it would be more cost-effective as electricity charges are lower and it would also save water, as evaporation is lower than during the daytime.

5.3. Current land-use practices and willingness of respondents to implement alternatives

The GTO-WCA is predominantly agricultural, with the highest number of irrigation farms in Namibia located in this area. Approximately 43% of the respondents farm with maize as their main crop (Table 4). The majority of these respondents practice crop rotation and irrigate throughout the year. According to the DWAF application form for irrigation, crop rotation is not considered in the applications for groundwater abstraction and applicants do not indicate that either, which is why respondents claim that their allocated quota is below the required amount. Water is allocated at 10,000m^3/ha/a. If a farmer wants to irrigate 10 ha, and the farmer gets a permitted allocation of $10 \times 10{,}000 = 100{,}000\ m^3$ and the farmer wants to plant two crops per annum, then the farmer can only cultivate 5 ha at a time, but the farmers do not follow this concept, and irrigate the entire size of the field. Permit conditions must be enforced by a competent resource manager that protects the groundwater resources by enforcing the law.

Most farms, especially in the Sub-region B2 and G, have been divided into smaller portions, making them unproductive for dryland cropping and also unsuitable for livestock farming. The majority of these portions of their land are cultivated, with 41% of farmers cultivating between 30 and 70% of their land, and with 35% cultivating more than 80% of their land. Approximately 65% of respondents are not willing to introduce crops that are less water-intensive, as the type of crops they are cultivating is determined by the market. The majority of the farmers are diversifying into cash crops to grow the business, but about 68% of respondents are willing to implement alternative land uses if water availability in the area deteriorates. They are however only willing to implement alternative land-uses once groundwater has been depleted to a point that irrigation cannot take place.

Table 4
Proportion of main crops produced in the study area.

Crop	Percentage produced in the study area
Maize	43%
Lucerne	13%
Carrots	11%
Potatoes	11%
Onion	8%
Peach	3%
Pearl millet	3%
Tomatoes	3%
Citrus	3%
Cabbage	2%
Total	100%

6. Conclusion

Groundwater is a finite resource and needs an integrated approach between the user, the planners, and the managers to ensure its sustainable management. This study showed that groundwater use allocation permits in the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area in Namibia are higher than the sustainable safe yield of these aquifers, and the actual permitted water use for irrigation is in most in-stances higher than the current sustainable use.

This non-alignment between water availability, permit allocation and water abstraction, is due to a complex mixture of amongst others, knowledge gaps on water availability and abstraction (officials manage water based on outdated data and models of more than 15 years old), and the fact that institutions (and the legal framework) is not yet adapted to current IWRM requirements. The policies and legislation in Namibia have not changed much since the Water Act, of 1956 and this

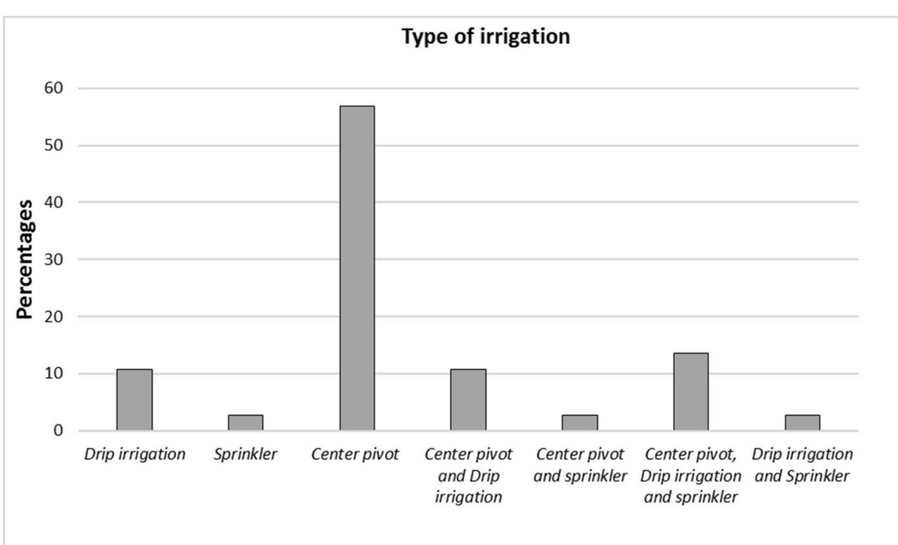

Fig. 5. Irrigation methods used by respondents.

lack of change has hampered sustainable water resources management (Blackie and Tarr, 2000). Existing legislation that incorporates IWRM (The WRMA of 2013) (Namibia, 2013) and its regulations and guidelines are not being enforced by the DWAF to control water abstractions and allocations, possibly because all the regulations under the WRMA of 2013 (Namibia, 2013) have not yet been promulgated. This survey confirms a high level of non-compliance to regulations by the farmers in the area. In addition, the groundwater model for managing water resources the area has not been updated, making the decision by DWAF to increase water allocations in the area, unsafe and unwise. Current water use is not included in the groundwater model, resulting in a poor understanding of water availability for future expansion. There are no punitive measures for non-compliance, making compliance voluntary instead of compulsory. A lack of financial resources has also been hampering compliance monitoring and enforcement in the area.

High water abstraction in karst aquifers during drought conditions when aquifer recharge does not occur to the degree that it should, can however irreversibly damage the aquifer structure and water storage capacity (Linares et al., 2017) as well as the aquifer's ability to transmit water (León and Parise, 2009). Groundwater over-abstraction in karst aquifers can also lead to the formation of sinkholes and land subsidence (Linares et al., 2017). Groundwater abstraction in this region is not sustainable under the current climatic conditions where severe droughts have been experienced from the 2012/13 to the 2015/16 seasons, with the 2015/16 season being the driest on record since the droughts of the early 1980s and 1990s (Archer et al., 2017).

From the above study, it is clear that there is a general lack of sustainable aquifer management and unsustainable aquifer abstraction. The following recommendations are made for consideration to improve the sustainable management of the aquifers in the GTO-WCA:

- There are various knowledge gaps in the GTO-WCA. Specific issues that must be addressed, include:
  - o There is a lack of updated groundwater information for the GTO-WCA. To address this knowledge gap, which creates uncertainty in understanding the system and which ultimately leads to uncertainty in how to manage the GTO-WCA, groundwater data must be updated.
  - o As part of addressing knowledge gaps, the Ministry of Agriculture, Water and Forestry must commission a study to determine the crop water requirement in the country, particularly in the GTO-WCA. This would help resource managers when allocating irrigation quotas to irrigation farmers.
  - o The Geohydrology Division at DWAF must develop a crop water requirement model and update the groundwater model, once the knowledge gaps on groundwater availability, water use, and crop water requirements have been addressed. This will enable the GTO-WCA to gain an understanding of minimum crop water requirements and water availability under current water use conditions, thereby ensuring more sustainable water use.
- On an institutional level, adaptive management approaches must be implemented to address uncertainties in data and water resources management more effectively (van der Voorn et al., 2012, 2017; Pahl-Wostl et al., 2008). The following specific institutional challenges must be addressed:
  - o The regulatory framework under the Water Resources Management Act of 2013, for water resources management in Namibia, must be finalised (outstanding regulations under the WRMA 2013 must be promulgated) to ensure that provisions under the WRMA are legally binding. This will ensure that IWRM practices currently implemented in the GTO-WCA are aligned with institutional arrangements, and will ensure that IWRM is better implemented at the GTO-WCA. The IWRM plan should also be actively endorsed and implemented in the water resources management sector. As part of IWRM, aspects such as water demand management, increased artificial recharge, and better water resources use monitoring must be further developed to address climate change concerns.
  - o The resource managers from DWAF must perform monitoring on the farms that are not complying with permit conditions and also do regulatory spot checks to verify data that is reported to the DWAF if it is correct. This monitoring must form part of the overall monitoring for the implementation of adaptive management.
  - o The BMC office must be strengthened by including a Hydrogeologist in the structure of the BMC to ensure that a knowledgeable individual in groundwater subjects manages matters of groundwater in the area.
  - o The KWMB must be re-established to more effectively monitor water use and allow the KWMB to influence water allocations. This will ensure the effective concentration of resources and management options for water management during integrated water resources management. Currently, the BMC is less effective in managing groundwater allocations and in conducting compliance monitoring than the KWMB was, as they lack key competencies.
  - o The legislation and policies by Geohydrology Division must be amended so that the management of Karst aquifers, including the allocation of abstraction quotas is clearly addressed. DWAF should increase human resource capacity and capacitate existing staff to effectively monitor and manage the water resources in the GTO-WCA.
  - o Information sharing to the farmers must be improved to change incorrect perceptions about groundwater availability and to promote sustainable groundwater use.
  - o A water payment or tax system must be implemented in the area. If users pay for the water, incentives of cheaper payment or lower taxes per volume of water used can be introduced, for users who introduce crops that are less water-intensive.
  - o Water inspectors must be re-introduced in the Directorate of Water Resources Management structures with an aim to improve and conduct effective compliance monitoring. The current structure gives the role of water policing to Technicians and Administrative officers who are not fully capacitated to deal with law enforcement matters.
  - o Resource managers should encourage farmers and all other water users to do resource monitoring that includes water level measurements, water quality testing and meter readings from the abstraction boreholes as indicated in the permit condition. This would enable the water users to understand the status of groundwater in their area over a long period.
  - o The water resources managers should raise awareness on a regular basis to create good relationships between them and the water users. This would enable the water user to gain trust in the resource managers.
  - o There should be a separation of powers between the water sector and the agricultural sector. Currently, the two sectors are headed by one Minister and most attention is given to food security and not much attention is given to water security. This is shown in the annual budget given to the two Departments, whereby the Agriculture Department get a disproportionately higher budget than the Water Department.
- Lastly, on a strategic level, future water resources management planning must be done for the GTO-WCA, to address external pressures on this water system, such as climate change, that will impact long-term water availability in the GTO-WCA. This can be done by performing scenario analysis (where an updated groundwater model can contribute tremendously), as well as by implementing adaptive management (AM) to incrementally change water resources management policies (van der Voorn et al., 2012; Pahl-Wostl et al., 2008). To ensure effective AM, proper assessment of the current GTO-WCA situation is required, followed by policy alignment (updating the Water Act and regulatory framework and aligning it with current IWRM practices). The implementation of an adapted

water resources management plan and monitoring of all newly implemented systems, to adapt water resources management if and where required (for instance, in response to climate change) is also necessary.

The uncertainties in the GTO-WCA (knowledge gaps), inaccurate allocation of permits, high levels of non-compliance with permit conditions and high levels of water abstraction from the karst aquifers, linked with an unwillingness to implement alternative land uses, boils down to groundwater mining. If the water resources policy and institutional arrangements are not more effectively aligned with IWRM, and if water resource managers do not perform their duties in the national interest to protect the groundwater resources over the longer term, irrigation farming will not be able to continue in this area and will go bankrupt. Karst aquifers in this region may then only recover in time if the aquifer structure has not been irreversibly damaged. In addition, the karst water in this region must also be reserved for supply to the central area of Namibia in future, which will become drier in future due to climate change. The Namibian government must, therefore, prevent karst aquifers from being destroyed by mismanagement.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2019.100295.

References

Angula, M.N., Kaundjua, M.B., 2016. The changing climate and human vulnerability in north-central Namibia. Jàmbá: J. Disaster Risk Stud. 8 (2).

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P., Marumbwa, F.M., 2017. Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. Clim. Risk Manag. 16, 22–28. https://doi.org/10.1016/j.crm.2017.03.006.

Ballweber, J.A., 2006. A comparison of IWRM frameworks: the United States and South Africa. J. Contemp. Water Res. Educ. 135 (1), 74–79.

Bann, C., Wood, S.C., 2012. Valuing groundwater: a practical approach for integrating groundwater economic values into decision making-A case study in Namibia, Southern Africa. Water S.A. 38 (3), 461–466. https://doi.org/10.4314/wsa.v38i3.12.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), 1997. Unpublished. Hydrogeology and Isotope Hydrology of the Otavi Mountainland and its Surroundings (KARST_01 and KARST_02), D-III, p. 65. BGR file no. 10793/97, BGR archive no. 116049; Windhoek.

Blackie, R., Tarr, P., 2000. Government Policies on Sustainable Development in Namibia. Population–Development–Environment in Namibia. http://wwwisis.unam.na/hivdocs/UNICEF/Namibia/Socio-economic/Population_development_environment%20_Namibia_pde_iiasa_2000.pdf#page=152.

Christelis, G., Struckmeier, W., Baumie, R., 2001. Groundwater in Namibia; an Explanation to the Hydrogeological Map. http://agris.fao.org/agris-search/search.do?recordID=XF2015022021.

Crawford, A., Terton, A., 2016. Review of Current and Planned Adaptation Action in Namibia. CARIAA Working Paper; No. 12. https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/55868/IDL-55868.pdf?sequence=1&isAllowed=y.

Dalin, C., Conway, D., 2016. Water resources transfers through southern African food trade: water efficiency and climate signals. Environ. Res. Lett. 11 (1), 015005 https://doi.org/10.1088/1748-9326/11/1/015005.

DWA (Department of Water Affairs), 1956. The Water Act, 1956 (Act 54 of 1956) as Made Applicable in South West Africa.

DWA, 1971. Regulation No. R1278. (Accessed 12 July 1971).

DWA, 1990. An Evaluation of the Groundwater Resources of the Grootfontein Karst Area, vol. 1990. Compiled by the Geohydrology Division, Department of Water Affairs, Ministry of Agriculture, Water and Rural Development.

DWA, 2004. Revised Criteria to be Considered when Allocating Permits for the Abstraction of Groundwater for Irrigation Purposes in the Tsumeb–Grootfontein–Otavi Subterranean Groundwater Control Area. Compiled by the Geohydrology Division, Department of Water Affairs, Ministry of Agriculture, Water and Rural Development, June 2004.

Garduno, H., Foster, S., 2010. Sustainable Groundwater Irrigation. Approaches to Reconciling Demand with Resources. Strategic Overview Series No. 4 World Bank. Washington. http://documents.worldbank.org/curated/en/603961468331259686/pdf/597000REVISED01WMATE0SO1412011April.pdf.

Giordano, M., Villholth, K., 2007. The agricultural groundwater revolution: setting the stage. In: Giordano, M., Villholth, K.G. (Eds.), The Agricultural Groundwater Revolution: Opportunities and Threats to Development. CABI International, Oxfordshire, pp. 1–4.

Gómez, V.M.R., Gutiérrez, M., Haro, B.N., López, D.N., Herrera, M.T.A., 2017. Groundwater quality impacted by land use/land cover change in a semiarid region of Mexico. Groundw. Sustain. Dev. 5, 160–167. https://doi.org/10.1016/j.gsd.2017.06.003.

Heyns, P., 2005. Water institutional reforms in Namibia. Water Policy 7 (1), 89–106.

Heyns, P., 2008. Application of a basin management approach to groundwater utilization in the Otavi Mountain Land, Namibia. Phys. Chem. Earth, Parts A/B/C 33 (8), 913–918. https://doi.org/10.1016/j.pce.2008.06.028.

Konikow, L.F., Kendy, E., 2005. Groundwater depletion: a global problem. Hydrogeol. J. 13 (1), 317–320. https://doi.org/10.1007/s10040-004-0411-8.

León, L.M., Parise, M., 2009. Managing environmental problems in Cuban karstic aquifers. Environ. Geol. 58 (2), 275–283. https://doi.org/10.1007/s00254-008-1612-6.

Liehr, S., Brenda, M., Cornel, P., Deffner, J., Felmeden, J., Jokisch, A., Kluge, T., Müller, K., Röhrig, J., Stibitz, V., Urban, W., 2016. From the concept to the tap—integrated water resources management in Northern Namibia. In: Borchardt, D., Bogardi, J.J., Ibisch, R.B. (Eds.), Integrated Water Resources Management: Concept, Research and Implementation. Springer International Publishing, Cham, pp. 683–717.

Linares, R., Roqué, C., Gutiérrez, F., Zarroca, M., Carbonel, D., Bach, J., Fabregat, I., 2017. The impact of droughts and climate change on sinkhole occurrence. A case study from the evaporite karst of the Fluvia Valley, NE Spain. Sci. Total Environ. 579, 345–358. https://doi.org/10.1016/j.scitotenv.2016.11.091.

MacKay, H., 2006. Protection and management of groundwater-dependent ecosystems: emerging challenges and potential approaches for policy and management. Aust. J. Bot. 54 (2), 231–237. https://doi.org/10.1071/BT05047.

Madramootoo, C.A., 2012. Sustainable groundwater use in agriculture. Irrig. Drain. 61 (S1), 26–33. https://doi.org/10.1002/ird.1658.

MAWF (Ministry of Agriculture, Water and Forestry), 2013. Water Resources Management Act, 2013 (Act 11 of 2013). Government of the Republic of Namibia, Windhoek.

MAWF, 2016. Groundwater Status of the Karst Area. Ministry of Agriculture, Water and Forestry. November 2016.Unpublished internal report.

MAWRD (Ministry of Agriculture, Water and Rural Development), 2000. National Water Policy White Paper. Ministry of Agriculture, Water and Rural Development, August 2000.

MAWRD, 2004. Water Resources Management Act, vol. 2004. Government of Republic of Namibia (Act 24 of 2004).

MET (Ministry of Environment and Tourism), 2015. National Climate Change Strategy and Action Plan. Ministry of Environment and Tourism, Windhoek. http://www.met.gov.na/files/files/National%20Climate%20Change%20Strategy%20&%20Action%20Plan%202013%20-%202020.pdf.

Namibia, 2010. Integrated Water Resources Management Plan for Namibia. Integrated Water Resources Management Plan for Namibia.

Namibia, 2013. Water Resources Management Act (Act 11 of 2013).

National Planning Commission, 2012. Namibia 2011 Population and Housing Census Preliminary Results. Windhoek, Namibia. https://www.google.com.na/search?q=National+Planning+Commission%2C+2012.+Namibia+2011+population+and+housing+census+preliminary+results.+Windhoek%2C+Namibia&oq=National+Planning+Commission%2C+2012.+Namibia+2011+population+and+housing+census+preliminary+results.+Windhoek%2C+Namibia&aqs=chrome..69i57.1027j0j7&sourceid=chrome&ie=UTF-8.

Pahl-Wostl, C., Sendzimir, J., Jeffrey, P., Aerts, J.C.J.H., Berkamp, G., Cross, K., 2008. Managing change toward adaptive water management through social learning. Ecol. Soc. 12 (2), 30.

Remmert, D., 2016. Water Governance in Namibia: A Tale of Delayed Implementation, Policy Shortfalls, and Miscommunication. Democracy Report – Special Briefing Report No. 13. http://www.the-eis.com/data/literature/Water%20governance%20in%20Namibia_2016.pdf.

RSA (Republic of South Africa), 1956. Water Act (Act 54 of 1956).

RSA, 1998. National Water Act (Act 36 of 1998).

Taheri, K., Taheri, M., Parise, M., 2016. Impact of intensive groundwater exploitation on an unprotected covered karst aquifer: a case study in Kermanshah Province, western Iran. Environ. Earth Sci. 75 (17), 1221. https://doi.org/10.1007/s12665-016-5995-5.

Theesfeld, I., 2010. Institutional challenges for national groundwater governance: policies and issues. Gr. Water 48 (1), 131–142. https://doi.org/10.1111/j.1745-6584.2009.00624.x.

Turpie, J., Midgley, G., Brown, C., Barnes, J.I., Pallett, J., Desmet, P., Tarr, J., Tarr, P., 2010. Climate Change Vulnerability and Adaptation Assessment for Namibia's Biodiversity and Protected Area System. Ministry of Environment and Tourism, Directorate of Parks & Wildlife Management.

van der Voorn, T., Pahl-Wostl, C., Quist, J., 2012. Combining backcasting and adaptive management for climate adaptation in coastal regions: a methodology and a South African case study. Futures 44 (4), 346–364.

van der Voorn, T., Quist, J., Pahl-Wostl, C., Haasnoot, M., 2017. Envisioning robust climate change adaptation futures for coastal regions: a comparative evaluation of

cases in three continents. Mitig. Adapt. Strategies Glob. Change 22 (3), 519–546. https://doi.org/10.1007/s11027-015-9686-4.
van der Voorn, T., Quist, J., 2018. Analysing the role of visions, agency, and Niches in historical transitions in watershed management in the lower Mississippi river. Water 10 (12), 1845.
Wanke, H., Dünkeloh, A., Udluft, P., 2008. Groundwater recharge assessment for the Kalahari catchment of north-eastern Namibia and north-western Botswana with a regional-scale water balance model. Water Resour. Manag. 22 (9), 1143–1158. https://doi.org/10.1007/s11269-007-9217-5.