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Chapter

Groundwater Dynamics in Transboundary Aquifers of Southern Africa

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Abstract

Groundwater resources are indispensable not only in water scarce or water stressed countries, but globally as a dependable reservoir and an alternative resource of freshwater. This study assessed the spatio-temporal variability of groundwater resources within two of the biggest transboundary aquifers that South Africa shares with its neighbouring countries. Groundwater dynamics in the Karoo-Sedimentary Transboundary Aquifer (KSTA) as well as the Stampriet Transboundary Aquifer System (STAS) were studied over a period of 72 years from 1948-2020. The study explored the use of historical groundwater storage data acquired through the use of Remote Sensing (RS) techniques, coupled with the use of Geographical Information Systems (GIS) to map spatio-temporal variability in groundwater storage. Groundwater resources of the Karoo-Sedimentary Transboundary Aquifer were found to be declining over time, with an overall decline of just over 5.4 km$^3$, whereas groundwater resources in the Stampriet remained relatively constant, with an overall increase of 0.2 km$^3$ over the past 72 years. The results show that RS techniques coupled with GIS applications are invaluable where there is a dearth of scientific data and information, furthermore, their use in the monitoring, management and protection of groundwater resources can be applicable on the local, regional and international scales.

Keywords: transboundary aquifer, southern Africa, groundwater, aquifer monitoring, Stampriet transboundary aquifer, Karoo sedimentary transboundary aquifer

1. Introduction

Water is a valuable commodity, not only for the human population, but also for all living as well as non-living biota. The availability of freshwater resources coupled with the quality of the available resource determines not only where life settles, but the quality of that life too [1].

Although nearly 70% of the surface of the earth is covered with water, over 90% of this is ocean water; an additional 2.2% is contained in ice sheets, glaciers and ice caps [2]. Therefore, according to Davies and Day [2], the fraction of water suitable for domestic use (potable water) is less than 1% of global water supplies. Furthermore, this proportion of freshwater is made up of atmospheric water, surface as well as groundwater resources [2]. With such limited availability, freshwater resources are not only
reserved for domestic use and the maintenance of aquatic ecosystems, benefits derived from available freshwater resources also include agricultural use, industrial production, mining as well as navigation, thus enabling and facilitating global socio-economic development. For this reason alone, global water security is of paramount concern.

Freshwater resources are, however, disproportionately distributed, where some areas have sufficient supplies of the resource, whereas the resource is gravely limited in other areas, thus threatening not only local or regional water security, but socio-economic advancement too. Moreover, freshwater resources are not only threatened by their natural distribution and availability, population growth coupled with economic expansion also increases the demand for freshwater resources worldwide. In addition, climate variability also threatens the supply and renewal of freshwater resources, more so in water-scarce areas, where extreme effects of climate change, such as droughts, will further exacerbate water scarcity. Although finite, freshwater resources are renewed through precipitation, which, similar to the distribution of freshwater supplies, is also disproportionately distributed. Thus, in order to protect the resource, it is important to safeguard the use of both surface and groundwater resources.

Groundwater resources are often utilised where surface water resources are limited, augmenting surface water supplies. Not only does groundwater supplement surface waters in arid and semi-arid areas, groundwater resources also sustain associated or hydraulically linked ecosystems through river base flows [3, 4], acting as a significant buffer in times of droughts [3, 5]. Thus, groundwater resources are fundamental to the Earth's supply of freshwater. These subsurface resources, which act as a natural reservoir for freshwater, are important for socio-economic development as well as the alleviation of poverty [6–8].

Groundwater resources provide the most dependable and most easily accessible source of freshwater in most arid and semi-arid areas with limited surface water supplies. Many socio-economic activities are reliant on groundwater resources, and over half the global population also relies on groundwater for their domestic supplies, where over 60% is used for agricultural irrigation, 25% is allocated for domestic use, and 10% is used by industry [9–11]. This allocation, however, differs from region to region, for example, groundwater augments drinking water in many developed countries, whereas, in semi-arid regions of the world, it serves as the main source of water [10]. According to Foster and Chilton [9], groundwater systems represent the world’s most predominant freshwater reservoirs. However, in many parts of the world, groundwater resources are excluded in the management of water resources, resulting in the overexploitation of the resource with no regard to its sustainability. Although out of sight, and often not easily quantifiable, groundwater resources should be monitored, conserved and efficiently managed to ensure their equitable and sustainable utilisation on national, regional and global scales; however, their subterranean nature makes this difficult to implement, especially where these resources traverse political borders.

1.1 Groundwater and aquifers

Groundwater is found below the surface of the earth, collecting in spaces in the soil and sediment and also filling up interstices between rocks [12]. These rock formations, together with the water stored within the crevices of the rock, are known as aquifers. Therefore, the shape and size of the spaces within the aquifer (rock formation) affect the total volume of water that can be stored in the spaces, a term referred to as porosity [13]. Moreover, in addition to an aquifer's storage capacity, an
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DOI: http://dx.doi.org/10.5772/intechopen.109906

Aquifer’s ability to diffuse water through the formation affects its yield [12, 14], a term referred to as permeability. Thus, according to Sophocleous [15], an aquifer’s permeability measures the connectivity of spaces within the aquifer, which allows for water to move through the aquifer. Aquifers can be superimposed by layers of soil, or other layers of rocks, and they may also sit on similar or different layers of rocks. These top and bottom layers may be permeable (allowing water to flow through the aquifer), thus known as aquitards or impermeable [allowing no movement of water through (into or out of) the aquifer] and, therefore, known as aquicludes (Figure 1).

Aquifers are, therefore, classified into three categories (unconfined, semi-confined and confined) based on their level of porosity and permeability. Unconfined aquifers are those aquifers where there is usually a hydraulic connection between surface and groundwater resources, or where there is connection between groundwater and water in the vadose (unsaturated) zone. A semi-confined aquifer (aquifer 2 in Figure 1) is an aquifer superimposed by a semi-permeable aquitard (thus allowing limited movement of water between the aquifer and the above environment) and underlain by an impermeable aquiclude, thus restricting the movement of water from below. A confined aquifer, often referred to as a “fossil aquifer,” is an aquifer that is completely closed-off, covered by an aquiclude on all the sides of the aquifer, thus completely closing off the water that saturated the aquifer during its formation [15]. As mentioned earlier, aquifers and their associated groundwater resources offer a vital relief in water-scarce areas, and similar to surface waters, these resources also cross political borders.

1.2 Transboundary aquifers

Transboundary aquifers (TBAs) are aquifers that are located beneath the surface of more than one country and are, thus, shared by those countries. Transboundary groundwater resources, therefore, sustain ecosystem services and ecological functions.
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of ecosystems reliant on groundwater in more than one country. Similar to national aquifers, transboundary aquifers are vulnerable to over abstraction and contamination; however, their exposure to pollution and risk of over abstraction increases with each border that the resource crosses. According to the International Groundwater Resources Assessment Centre (IGRAC), approximately 468 transboundary aquifer systems have been identified worldwide, as depicted in Figure 2. Of these, 135 transboundary aquifers were identified in the Americas, 130 in Asia, 106 in Africa, and 97 in Europe [17].

Of the 106 transboundary aquifers found in Africa, 24 aquifers are shared by the 12 states representing the Southern African Development Community (SADC): Angola, Botswana, Democratic Republic of Congo, Eswatini, Lesotho, Malawi, Mozambique, Namibia, Tanzania, South Africa, Zambia and Zimbabwe (Figure 3).

Of the 24 transboundary aquifers found within the SADC region, nine are shared by South Africa and its neighbouring states. The study, however, focuses only on two of the biggest transboundary aquifers shared by South Africa and its neighbouring countries. The study focuses on the Karoo Sedimentary Transboundary Aquifer (KSTA) shared by South Africa and Lesotho, as well as the Stampriet Transboundary Aquifer System (STAS), shared by Botswana, Namibia and South Africa (AF1 and AF5 in Figure 3).

1.3 Remote sensing (RS) techniques and geographical information system (GIS) applications in groundwater studies

The use of earth observation applications has recently gained momentum [18–23]. The techniques offer unique opportunities to simultaneously study large surface areas, making it possible to extrapolate and correlate isolated spatial data. Moreover, earth observation techniques can provide large-scale (regional or even global) information that would otherwise be impossible to collate in a short space of time. Thus, these techniques make it possible to study variations in groundwater storage (GWS) in areas where ground-based data are not available, as well as for inaccessible areas. The availability of earth observation applications coupled with the advent and popularity of geographic information systems (GIS) has made investigations in
Groundwater studies a possibility in largely arid and semi/hyper-arid locations where the skills for ground-based observations are not available [24–27].

Spatio-temporal remote sensing provides global near-real-time, automated, cost-effective data that are accessible and accurate [24, 28–31]. The aim of this study was to explore the use of remote sensing (RS) techniques, coupled with the application of geographical information systems (GIS) to assess the spatio-temporal variability of groundwater resources of the Karoo Sedimentary Transboundary Aquifer as well as the Stampriet Transboundary Aquifer System.

2. Materials and methods

Southern Africa is a semi-arid region characterised by low and erratic rainfall, occasional flooding, high evaporation rates, cold winters and prolonged droughts [2]. The region is mostly underlain by the 2.5 million km$^2$ Kalahari Basin [32] and the 500,000 km$^2$ Karoo Basin [33]. The Karoo Basin covers the entirety of the Kingdom of Lesotho, and most of South Africa, whereas the Kalahari Basin is located in parts of Angola, most of Botswana, small patches in the Democratic Republic of Congo, some parts of Eastern Namibia and parts of the Northern-Cape in South Africa, as well parts of Zambia and small patches in Zimbabwe [34]. The KSTA is located within the Karoo Basin, and the STAS is located within the Kalahari Basin.

2.1 The Karoo Sedimentary Transboundary Aquifer

The Karoo Sedimentary Transboundary Aquifer (KSTA) is 165,936 km$^2$, covering all of Lesotho, most of the Eastern Cape, and parts of Kwa-Zulu Natal, the Free State and the Northern Cape provinces in South Africa (Figure 4). It is the largest TBA between South Africa and a neighbouring state, with an estimated population of just approximately 2.2 million people [35].

Figure 3.
Map of the 24 transboundary aquifers located in the SADC region.
2.2 The Stampriet Transboundary Aquifer System

The Stampriet Transboundary Aquifer System (STAS) is 102,401 km² and straddles the shared border between Botswana, Namibia and South Africa. Most of the aquifer is in central Namibia, which accounts for 73% of the surface area and just over 90% of the population (total population estimated at 50,000) [36]. Botswana makes up 19%, while a small part of the Northern Cape in South Africa (which is entirely a National Park) constitutes the rest (Figure 5). The aquifer is named after the village of Stampriet, which is located in Hardap, Namibia.

The two transboundary aquifers are located below the Orange-Senqu transboundary river basin shared by Botswana, Lesotho, Namibia and South Africa (Figure 6). The majority of the Karoo Sedimentary TBA lies beneath the Orange-Senqu River Basin, while the entire Stampriet TBA system is located beneath the transboundary river basin, with some of the upper aquifers hydraulically linked to the basin, whose management, conservation, governance, protection and development are administered through the Orange-Senqu River Commission (ORASECOM).

2.3 Groundwater storage

The study used National Aeronautics and Space Administration (NASA)’s Goddard Earth Sciences Data and Information Services Center (GES DISC) to access and download data used in the study. NASA’s Goddard Earth Sciences Data and Information Services Center developed the Goddard Interactive Online Visualisation and analysis Infrastructure or “Giovanni.” Giovanni is an application that allows the visualisation of selected geophysical parameters [37]. It supports
single- and multi-parameter visualisations as well as statistical analysis, providing an interactive interface for comparing data from a multitude of sources [37]. The data used in the study were accessed and downloaded from Giovanni. Groundwater storage data were retrieved from the Global Land Data Assimilation System Version 2 (GLDAS-2), which currently covers data from January 1948 to March 2022. The study utilised data from January 1948 to December 2020, covering a span of 72 years.
The study utilised gridded GLDAS Model CLMS025 groundwater storage data maps of 0.25° resolution (27.2 km) to map groundwater storage in the two selected aquifers in Southern Africa. Groundwater storage (GWS) is calculated by subtracting snow water equivalent (SWE), root zone soil moisture (RZSM), and canopy interception storage (CIS), from the total water storage (TWS), using Eqs. (1) and (2) below.

\[
TWS = CIS + GWS + RZSM + SWE
\]

Thus,

\[
GWS = TWS - CIS - RZSM - SWE.
\]

Annual data (January–December 1948) were downloaded as raster image files, showing the total groundwater storage for that year [38, 39]. Data for subsequent years (1949–2020) were also downloaded.

A geographical information systems’ application was used for the extraction and manipulation of the data. Before the extraction of data, shapefiles for each aquifer were created, and these were saved as vector files. For each of the study area aquifers, a shapefile was used for masking/clipping the GLDAS-gridded raster images. For each aquifer, groundwater storage data were extracted in 10-year intervals for a period of seven decades (1948–2018), a total of 72 years when including the years 2019 and 2020.

The raster images for two periods to be compared (e.g., 1948 and 1958) were differenced using the map algebra function in the GIS application. This involved subtracting the raster 1948 from the 1958 raster. The differenced map represents the change in storage for that period. The maps showing the change in groundwater storage for each aquifer and the surrounds were saved as .PNG files, and the images are presented in Section 3, showing areas of significant recharge and discharge in each study area. The storage data are provided in the raster file as depth in millimetres. The depth was converted to volume in cubic kilometres using the following Eq. (3) below:

\[
\text{Volume} (\text{km}^3) = \frac{\text{depth} (\text{mm})}{1,000,000} \times \text{Area of the aquifer} (\text{km}^2).
\]

1 km = 1,000,000 mm; hence, in (2), there is division by 1,000,000 in order to convert the millimetres to kilometres.

Since each raster image grid cell size in this case is 0.25° × 0.25°, which is equivalent to 27.2 km × 27.2 km, the size of each grid is, therefore, an area of 739.84 km². This area was multiplied by the number of grid cells for each study area in order to calculate the size of each aquifer.

For the purposes of this study, groundwater is defined as subsurface freshwater found within confined and unconfined aquifers. Thus, changes in groundwater depth refer to changes in the depth of the water table, whereas changes in groundwater volume refer to changes in the volume of groundwater within the demarcated area of each transboundary aquifer. Moreover, mentioning groundwater volume or storage capacity of the Karoo (KSTA) or the Stampriet (STAS) refers to the volume of groundwater within each aquifer/aquifer system.
3. Results and discussion

The insufficient availability of groundwater data (such as storage, quality and recharge and discharge patterns) results in a knowledge gap regarding the variability of groundwater resources globally. This is exacerbated by overexploitation as well as contamination that is usually unaccounted for and that can also go unnoticed for decades.

Thus, the limited information on the quantity (availability) and quality (contamination) of groundwater resources, coupled with anthropogenic activities as well as climate change, threatens the protection and management as well as the sustainable use of groundwater resources [40]. Accordingly, the use of earth observation or remote sensing techniques in monitoring groundwater resources has become invaluable in groundwater monitoring studies.

3.1 The Karoo-Sedimentary Transboundary Aquifer (KSTA)

Groundwater storage within the area of the Karoo Sedimentary aquifer is depicted in Figure 7. The volume of groundwater is presented over a period of 72 years, from the 1 January, 1948 to 31 December, 2020.

The volume of groundwater in the area fluctuated (between 95 and 120 km$^3$) throughout the study period, showing periods of decreasing and increasing volumes, with 1975 and 1978 depicting higher volumes of 128 and 134 km$^3$, respectively. The aquifer's largest increase in volume was recorded between 1970 and 1980, and again between 2000 and 2010, with the largest decrease in volume recorded between 2010 and 2020. The monthly fluctuations in groundwater volume are depicted in Figure 8.

Groundwater volumes were higher between January and July where average volumes were above 105 km$^3$. There was a steady decline in average volumes between August and November each year, and volumes start to increase again in December each year. These seasonal fluctuations in groundwater volumes correspond to the rainy season in the region. The region receives summer rainfall, starting in December through to March/April each year.

3.1.1 Spatial changes in groundwater resources of the KSTA

The KSTA is the largest transboundary aquifer that South Africa shares with a neighbouring state. Thus, changes in groundwater storage will not be uniform throughout the entire surface area of the aquifer. During a given period, some areas of the aquifer may experience increased recharges, whereas other areas of the same aquifer experience a discharge. Figure 9 shows the spatial variation in groundwater storage depth of the KSTA.

Figure 9 shows how the depth of groundwater in the aquifer changed over time. Areas that increased in depth as well as areas where depth was reduced are depicted across the aquifer. The figure shows that large parts of the aquifer experienced a decline in groundwater storage depth between 1978 and 2007. The figure also shows that recharge and discharge is not uniform throughout the surface of the aquifer. Moreover, even though there was some form of discharge of groundwater from the aquifer between 1948 and 1967, at that time discharge occurred in small areas. Furthermore, between 1948 and 1957, large discharge of groundwater occurred in parts of the Free State, the Eastern Cape, as well as small areas around the border of the Northern Cape Province (refer to Figure 4 showing the location of the aquifer), as revealed by the negative changes in groundwater depth.
In the same decade, positive changes in depth were observed throughout the entire surface of the aquifer; however, increased recharge occurred largely in Lesotho. In the next decade, it can be seen from Figure 9 that areas of discharge covered the north-eastern parts of the aquifer and became more pronounced in Lesotho, spreading to neighbouring parts of the Eastern Cape as well as Kwa-Zulu Natal, whereas recharge was observed throughout the remaining area of the aquifer. This changed again between 1968 and 1977, with the decade experiencing the
highest recharge (largest positive changes in groundwater depth) recorded in the study. Although the decade (1968–1977) was dominated by higher recharge and low to almost non-existent discharge, this was short-lived. The rate of discharge (shown by the decreasing depth of water in the aquifer) increased and eventually became higher than the rate of recharge (which is represented by increasing depth) in the subsequent years from 1978 to 2007. Areas of recharge currently account for less than 10% of the total surface area of the Karoo transboundary aquifer. The graph also shows that the largest discharge of groundwater from the Karoo aquifer occurs in Lesotho. Similar conclusions were reached in previous studies in California [41, 42], China [43, 44], India [45–50], Iran [51], the Indus Basin transboundary aquifer [52], Kenya [53] and the North-Western Sahara Aquifer System (NWSAS) [54], where groundwater storage was found to be declining over time.

3.2 The Stampriet Transboundary Aquifer System (STAS)

Groundwater storage within the area of the Stampriet aquifer is depicted in Figure 10. The volume of groundwater in the area is presented over a period of 72 years, from 1 January, 1948 to 31 December, 2020.

The volume of groundwater fluctuated between 30 and 37 km$^3$, with some years (1950–1951, 1954–1955, 1957–1958, 2000–2001, and 2005–2006) depicting volumes above 37 km$^3$. The volume of groundwater in the aquifer fluctuated throughout the study period, showing periods of declines and increases in volume. The aquifer’s largest increase in volume was recorded between 1970 and 1980, and the largest decrease was recorded between 1980 and 1990. Moreover, the largest volumes of groundwater were recorded between 1975 and 1978, where values were above 45 and 47 km$^3$, respectively. The monthly fluctuations in groundwater volume are depicted in Figure 11.

Groundwater volumes were higher between January and July where average volumes are 33 km$^3$ or above, with a slight decline in average volumes recorded between August and December each year.
3.2.1 Spatial changes in groundwater resources of the STAS

Similar to the KSTA, the STAS is also large; thus, changes in groundwater storage will not be uniform throughout the entire surface area of the aquifer. The spatial changes that occurred in the Stampriet (STAS) are depicted in Figure 12, showing how the depth of groundwater in the aquifer changed over time.

Areas that increased in depth as well as areas where depth was reduced are depicted across the aquifer. Although Figure 12 shows that large parts (approximately
90%) of the aquifer experienced a decline in storage depth between 1978 and 1987, areas of recharge increased between 1988 and 2007. During the first decade of study (1948–1957), the Stampriet was dominated by areas of recharge (0.1–50 cm increase in depth), with a small portion of the aquifer showing points of discharge (−24.1 to 0.1 cm decrease in depth) nested along the border of Botswana and South Africa (Figure 12). In the next decade (1958–1967), areas of discharge increased and included parts of the aquifer underlying Namibia. The largest positive change in storage depth (increase in depth) occurred between 1968 and 1977, with large areas of the aquifer experiencing increased depth, and only a small part of the aquifer experiencing a minimal decrease in depth. The greatest loss in storage in the Stampriet were recorded between 1978 and 1987, where only a small portion of the aquifer recorded an increase in depth, whereas the remaining parts of the aquifer experienced a loss in depth. Some areas of the aquifer recorded losses of 50 cm and above, with some areas also recording losses above 100 cm. A period of recovery was documented between 1988 and 1997 in Namibia, where the majority of the aquifer's surface area depicted an increase in depth, whereas decreasing depths were observed in parts of the aquifer underlying Botswana, South Africa as well as some parts of southwestern Namibia. Although there were periods when the Stampriet recorded large reduction in depth (1978–1987), the overall positive change in depths reflects increased recharge. The two aquifers mentioned above have experienced fluctuations in groundwater depth and volume over the 72-year study period. Both the aquifers experienced an increase in depth between 1968 and 1977, whereas the largest losses were recorded in both aquifers between 1978 and 1987.

3.3 Conservation, development and management of the KSTA and the STAS

The governments of the Republic of Botswana, the Kingdom of Lesotho, the Republic of Namibia and the Republic of South Africa established the Orange-Senqu River Commission Agreement (ORASECOM agreement) on 3 November, 2000 [55]. The agreement was founded on the Helsinki Rules [56], the UN Watercourses
Convention [57] as well as the revised SADC protocol on shared water resources [58], with the aim of serving as technical advisor to the parties on matters relating to the development, utilisation and conservation of the water resources of the Orange-Senqu Basin [55].

The ORASECOM agreement lists cooperation as the first obligation of the parties, as stipulated in article 7(1) of the agreement. The obligation to cooperate is an important provision, as it makes it possible for member states to jointly develop, conserve and govern their shared water resources in order to achieve mutual benefit. In addition to the obligation to cooperate, the ORASECOM agreement imposes on member states a duty to protect and preserve the ecosystem of the Orange-Senqu watercourse, article 7(12) of the agreement also imposes a duty on member states to individually and jointly take all the relevant measures to protect and preserve the river system from its sources and headwaters to its common terminus, and article 5(2)(6) imposes a duty to control and reduce pollution. Article 7(2) of the agreement further imposes a duty on watercourse states to utilise the resources of the transboundary catchment in an equitable and reasonable manner in line with the 2000 revised SADC protocol, with a view to attaining an optimal and sustainable use of the resource, in order to ensure its protection.

Member states are further instructed to take all suitable actions to avoid the causing of significant transboundary harm to any other party in line with the revised SADC protocol. The ORASECOM agreement further imposes on member states a duty to include an environmental impact assessment (EIA) study as part of their due diligence and to also address the possible effects of any planned activity on the social, cultural, economic as well as the natural environment. Reflecting the 1997 watercourses convention, as well as the 2000 revised SADC protocol, the ORASECOM agreement also stipulates in articles (7(5-11, and 16) the rules and procedures to be followed by member states in planning and implementing activities (within their territories), which might have adverse effects on the shared watercourse or on other member states.

The ORASECOM agreement established the commission on the Orange-Senqu Basin. Through cooperation, the commission is able to protect and manage their shared water resources in an equitable and sustainable manner with the consideration of each member state’s interest in the shared resource. In addition to the legal status of the commission stipulated in the first article of the agreement, the agreement also makes provision for member states to establish river commissions with regard to any part of the Orange-Senqu (article 1(4) and further states that such agreements will be subordinate to the ORASECOM agreement. Furthermore, the agreement makes provision for the establishment of joint commissions and committees on the protection, conservation, development and governance of their respective watercourses. As a result, the ORASECOM established the Groundwater Hydrology Committee (GWHC), which is responsible for all the groundwater-related matters of the Orange-Senqu Catchment (ORASECOM, 2021), thus making provision for the protection and governance of shared groundwater resources through the joint committees of cooperation.

In May 2017, ORASECOM’s Groundwater Hydrology Committee (GWHC) as well as the Technical Task Team (TTT) supported the proposal to establish within the ORASECOM structure a multi-country cooperation mechanism (MCCM) for the governance and management of the Stampriet Transboundary Aquifer System [59]. The MCCM is meant to facilitate cooperation among states in the development, monitoring, governance and management of the STAS [59, 60]. The cooperation mechanism
was established as part of the STAS–Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) Project with the aim of the mechanism becoming a joint mechanism advising member states on the management of the STAS [59].

The results of the study show that there is great spatio-temporal variability in the groundwater resources within the two transboundary aquifers shared by South Africa and its neighbouring countries. Moreover, the seasonal variability in groundwater resources in the two transboundary aquifers is in line with findings from previous studies that found that groundwater variability is largely influenced by climatic variations [61–66], predominantly precipitation [67, 68], as well as evapotranspiration [69, 70]. Moreover, as shown in previous studies [18, 45, 61, 71–81], data acquired through remote sensing techniques can be exceptionally applicable in hydrogeological studies where in situ data are insufficient.

Furthermore, in addition to the ORASECOM Groundwater Hydrology Committee, the cooperation mechanism mentioned above is the first governance mechanism to ever be incorporated in a river basin organisation, making it possible for the commission to manage the water resources of the Orange-Senqu conjunctively, following Integrated Water Resources Management (IWRM) processes.

Since only six international agreements and arrangements have been concluded on the utilisation, sound management and governance of over 400 transboundary aquifers globally, compared to over 3600 agreements and arrangements that have been signed on the 279 shared surface waters [82], the law regulating transboundary groundwater resources is, thus, gravely lagging and, as such, still in its initial stages. Therefore, through the establishment of joint commissions such as the multi-country cooperation mechanism responsible for the development and management of the STAS, the equitable use and sustainable management of transboundary groundwater resources is possible not only in South Africa, but globally too.

The study has shown that incorporating the management of groundwater resources through the establishment of groundwater specific committees within existing surface water agreements can ensure the protection, as well as manage equitable and sustainable utilisation of shared groundwater resources.

4. Conclusions

Monitoring groundwater resources using remote sensing techniques alleviates the pressure on the routine monitoring of sparsely distributed monitoring wells. Moreover, the use of satellites allows for the acquisition of data at spatio-temporal scales that would otherwise be inaccessible.

Although the historical data used in the study do not take into consideration anthropogenic impacts on changes in groundwater storage, the results show that groundwater resources in the region are declining, and these changes can be attributed to the effects of climate change.

Thus, with improved monitoring (taking into consideration anthropogenic activities) coupled with sound management, the protection, conservation and sustainability of groundwater resources in Southern Africa may be improved.

The study shows that the poor management of water resources (local, regional and international) as a result of the lack of data and information as well as the lack of resources (human, financial and infrastructural) can be overcome with the use of

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remote sensing techniques coupled with the application of geographical information systems. The results obtained in this study are applicable at all spheres of water management and governance (freshwater resources including both surface and groundwater resources, as well as brackish and marine water resources), from the local, municipal, provincial, national as well as regional and international scales. Moreover, similar results can be achieved in other fields of study too wherever RS data are available and accessible and where GIS is applicable.

Acknowledgements

The author would like to thank NASA’s Goddard Earth Sciences Data and Information Services Center for making the data available and accessible, augmenting data where it would otherwise not be available and thus enabling research.

Conflict of interest

The author declares no conflict of interest.

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DOI: http://dx.doi.org/10.5772/intechopen.109906


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