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Recent Advances with the Integrated Hydrological Model of the Stampriet Transboundary Aquifer System (STAS)

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Abstract.

The STAS is a large transboundary aquifer system (>120 000 km²) shared between Botswana, Namibia, and South Africa. It provides the only water resource in this arid region. As part of the GGRETA project, UNESCO and local stakeholders have been promoting the development of a groundwater model for the assessment and the sustainable management of this shared resource. In this communication, we retrace recent progress and lessons learnt from this modelling project. First, a detailed hydrostratigraphic study allowed us to refine the geometry of the STAS and in particular the position of its boundaries. This study also highlighted links between the STAS and the neighboring Central Kalahari Basin. To the south, a large complex of salt pans was identified as the regional outlet for the basin (Hakskeen, Koppieskraal, Uitsak pans). Second, although the isotope data for the basin were compiled in phase 1 of the GGRETA project, they had, to date, never been used as information for the STAS numerical model. Integration of environmental tracer data allowed the identification of key hydrological recharge, discharge, and aquifer exchange processes. In particular, the hydrochemical and isotopic synthesis highlighted the importance of land surface and groundwater interactions. In turn, this led us to select an integrated hydrological model capable of simulating interaction between land surface (UZF; Niswonger et al. 2006) and groundwater (MODFLOW). A feasibility study showed there would be great benefits moving from a former stand-alone model, which requires manual updating, to a state-of-the-art integrated modelling platform that can be shared by all stakeholders and updated automatically with remote sensing data.

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Introduction

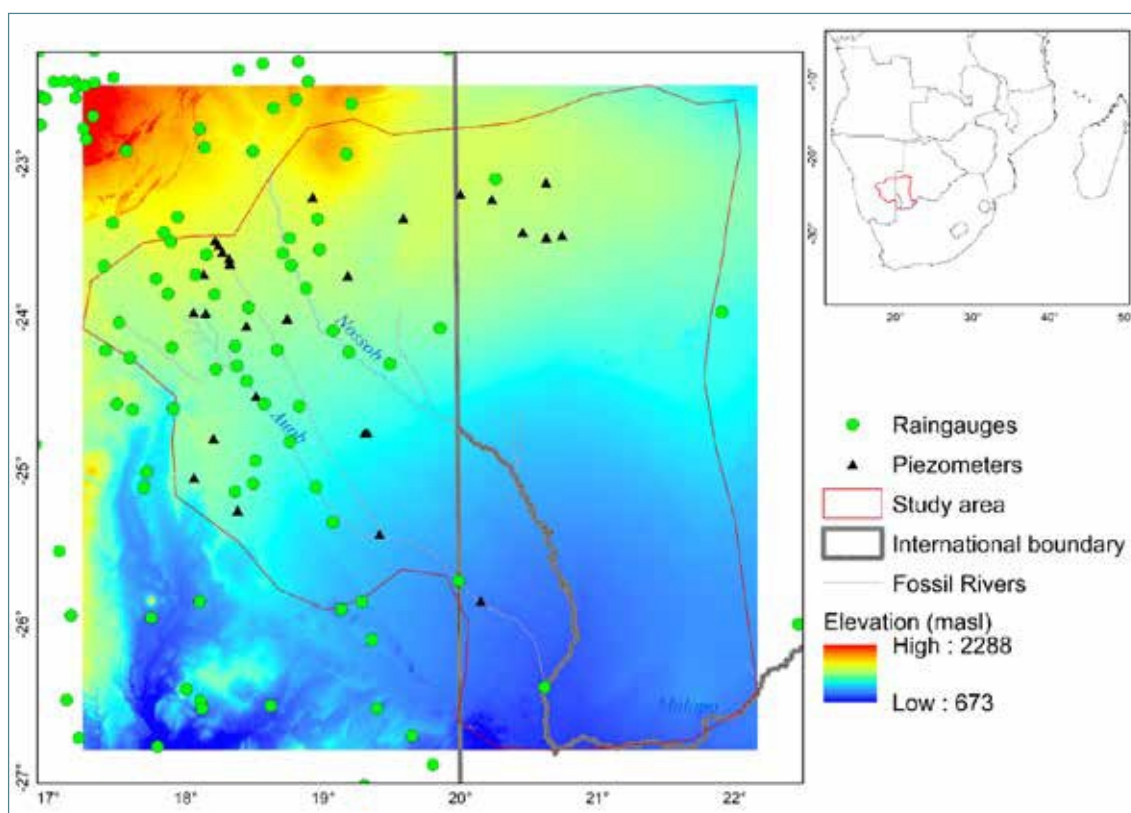
GGRETA is an international project aimed at gaining experience in Governance of Groundwater Resources in Transboundary Aquifers. GGRETA is funded by the Swiss Agency for Development and Cooperation (SDC) and is implemented by the UNESCO International Hydrological Programme (UNESCO-IHP) in close partnership with the International Union for Conservation of Nature (IUCN), the UNESCO International Groundwater Assessment Centre (IGRAC) and local project teams. GGRETA has three pilot studies of Transboundary Aquifer (TBA) systems: the Trifinio aquifer in Central America, the Stampriet aquifer system in Southern Africa and the Pretashkent aquifer system in Central Asia.

In the context of the GGRETA project, the objectives for STAS were to address key issues relating to (i) hydrogeological perspectives -i.e., defining among others, system boundaries and aquifer extent, main aquifers of the STAS, status of groundwater quality and quantity and establishing a groundwater modelling framework for the area; (ii) socio-economic and environmental components (groundwater use, level of sanitation, and pollution sources); (iii) legal and institutional components (status of

domestic laws/legislation and institutions used to manage groundwater in each of the three STAS countries), as well as highlighting the existing regional legislations/frameworks for groundwater management in the SADC region; and (iv) gender considerations, i.e., documenting the degree of gender considerations in the management of groundwater in the STAS (UNESCO, 2016; Kenabatho et al., 2021).

The Stampriet Transboundary Aquifer System stretches from Central Namibia into Western Botswana and South Africa's Northern Cape Province and lies within the Orange River Basin (Fig.1). It covers an area of over 120,000 km². The topography of the area is relatively flat with an elevation of 1500 m to 900 m above mean sea level from the northwest to the southeast. Rainfall normally occurs between October and April predominantly in the form of thunderstorms (high intensity and short duration) and ranges between 150 to 250 mm. The highest rainfall months are from January to March whilst the lowest months are from June to September. Potential evapotranspiration is as high as 3800 mm in the southern part of the basin, and in normal years little or no local runoff is generated (UNESCO, 2016).

Fig. 1.
Location of the Stampriet Transboundary Basin



(© Own Elaboration)

Hydrostratigraphy and aquifer geometry

Different nomenclature is used to describe geology in various sub-basins of STAS. For instance, the nomenclature adopted in the SW Botswana sub-basin follows Smith et al., (1984) while Aranos and Kalahari Gemsbok in South Africa follows SACS (1980) nomenclature. It was therefore important to harmonize the nomenclature and definition of the hydrostratigraphic units across the basin. This process involved revision of lithology of every borehole in order to classify them into the appropriate hydrostratigraphic units. The hydrostratigraphy of STAS was classified into six units including the unconfined Kalahari and Lebung aquifers, the Inter-Karoo Aquitard, Auob Aquifer, Mukorob Aquitard and Nossob Aquifer (Table 1; Kinoti et al., submitted).

The result of this work on the STAS hydrostratigraphy and 3D geometry under the GRETA project will be published shortly in a paper (Kinoti et al., submitted) and can be summarised as follow:

- the size of the STAS is increased by 25% compared to the previous study (Fig. 1).
- Studies conducted in various sub-catchments of STAS adopted different nomenclature and thus the first and most important step was to harmonize the stratigraphic units across the basin (Table 1).
- Inclusion of faults in the 3D geological model revealed that the groundwater flow system in the basin is not entirely influenced by surface topography but is also influenced by regional faults.

- 3D geometry provided a first estimate of groundwater reserves for the 4 aquifers. Based on specific yield and storage coefficient estimates and volume of each aquifer, groundwater resources of STAS range between 3 to 5.1×10^{12} ; 2.1 to 7.3×10^{11} ; 1.7 to 6.1×10^{12} and 4.5 to 2.6^{11} m^3 for Kalahari, Lebung, Auob and Nossob aquifers, respectively. More accurate estimates will be obtained from the numerical model.

Table 1
Stratigraphy and hydrostratigraphy of STAS, modified

Description Period	Super Group	Group	Region					Hydrogeological layers
			Mariental-Asab area (1)	Vreda Area (2)	South-East (3)	Ncojane (4)	Matlho-a-Phuduhudu	
Tertiary to Quaternary	Post-Karoo	Kalahari	Kalahari group					Kalahari Aquifer
Cretaceous to Jurassic	Upper Karoo	Karoo Basalts & Dolerites	Kalkrand Basalts	Karoo Dolerites		Doodoog Formation	Ntaor Sandstone	Lebung Aquifer
Triassic		Lebung	Rietmond Member					
Upper Permian	Lower Karoo	Rietmond	Rietmond Member			Upper Kobe Formation	Inter Karoo Aquitard	
Lower Permian		Ecca	Auob Member	Mukorob Member				Otshe Formation
			Mukorob Member	Mukorob Member		Upper Kobe Formation	Mukorob Aquitard	
Mesoproterozoic	Dwyka	Dwyka	Nossob Member		Nossob Sandstone	Lower Kobe Formation	Nossob Aquifer	
			Dwyka Group					Beaufort Aquitard
Archaean	Pre-Karoo		Nama and Damara		Olanos Complex			

(Kinoti et al., submitted)

Environmental tracers

As part of the GGRETA project we conducted a synthesis of environmental tracer data in the Stampriet Transboundary Aquifer System. The hydrochemistry data (including 807 TDS values, 713 Cl/Br ratios, 692 NO₃/Cl ratios, 73 radiocarbon, 54 tritium, and 108 18O and 2H values) was collated from many previous works in the region (from the Ministry of Agriculture, Water and Forestry in Namibia, Department of Water and Sanitation in Botswana, and Department of Water and Sanitation in South Africa, and Kirschner et al., 2002), and was compiled for the UNESCO GGRETA 1 project. We mapped and analysed the multiple environmental tracers to help inform on the conceptual model of the Stampriet Basin. In particular, we used information from the environmental tracer data to improve our

understanding of recharge, discharge and inter-aquifer mixing processes for the Kalahari, Auob and Nossob aquifers. A summary of the processes identified is presented below.

Recharge Processes

Groundwater is mostly recharged during high rainfall levels (≥ 200 mm/month; as indicated by ¹⁸O and ²H values), which are rare events. For example, during a 38-year rainfall monitoring period, rainfall ≥ 200 mm/month occurred only 4 times (Jan-94, Jan-97, Jan-06 and Feb-09). The groundwater flow is slow resulting in mean ¹⁴C residence times ranging up to 22100, 39000 and ≥ 40000 years in the Kalahari, Auob and Nossob aquifers, respectively. ¹⁴C mean residence times show no clear trends with regional flow pathways in each of the aquifers and are likely impacted by heterogeneous inter-aquifer

mixing processes. In the northern section of the Auob and Nossob aquifers, there are even areas where groundwater represents paleorecharge conditions, and therefore reflects even slower flow rates compared to the rest of the basin.

Evaporation and transpiration processes

Results from the ^{18}O and ^2H values highlight that all groundwater sampled were impacted by evaporation, and that transpiration was a less dominant process. From the environmental tracer data, it was not evident whether evaporation occurs directly from the water table, and/or whether the evaporated ^{18}O and ^2H signature is the result of mixing with infiltrating waters evaporated in the unsaturated zone.

Inter-Aquifer Mixing Processes

This study includes an area where the environmental tracer data (TDS, ^{18}O and ^{14}C values) indicates flow in both directions between the Kalahari and Auob aquifers. Aquifer vertical flow exchange in this area is also supported by the long-term hydraulic head data (over a 9-year monitoring period) that show declines in the hydraulic heads of the Auob aquifer relative to the more stable Kalahari aquifer. Therefore, there has been a reversal of the vertical hydraulic gradient between the Kalahari and Auob aquifers from upward to downward direction. The mixing zones between the Kalahari and Auob aquifers identified from the environmental tracer data show some correlation with the Inter-Karoo aquitard thickness (5 of the 14 mixing zones have an aquitard thickness $\leq 3\text{m}$), and a higher correlation with the location of faults (8 of the 14 mixing zones have faults that pass nearby the mixing zone).

Automated update of the STAS groundwater model with remote sensing

The STAS integrated hydrological model requires daily rainfall data as a driving force. Rain gauges are scarce in the STAS and observations are not available in real time. Hence satellite rainfall estimates provide an effective alternative (Satge et al., 2020) and are used as input data for the model. Here we selected data from IMERG, which combines information from the Global Precipitation Measurement (GPM) constellation (<https://gpm.nasa.gov/data/imerg>; Huffman et al. (2021)). The latest Version 06 release of IMERG, which is used here, fuses the early precipitation estimates collected during the operation of the TRMM satellite (2000-2015) with more recent precipitation estimates collected during operation of the GPM satellite (2014-present).

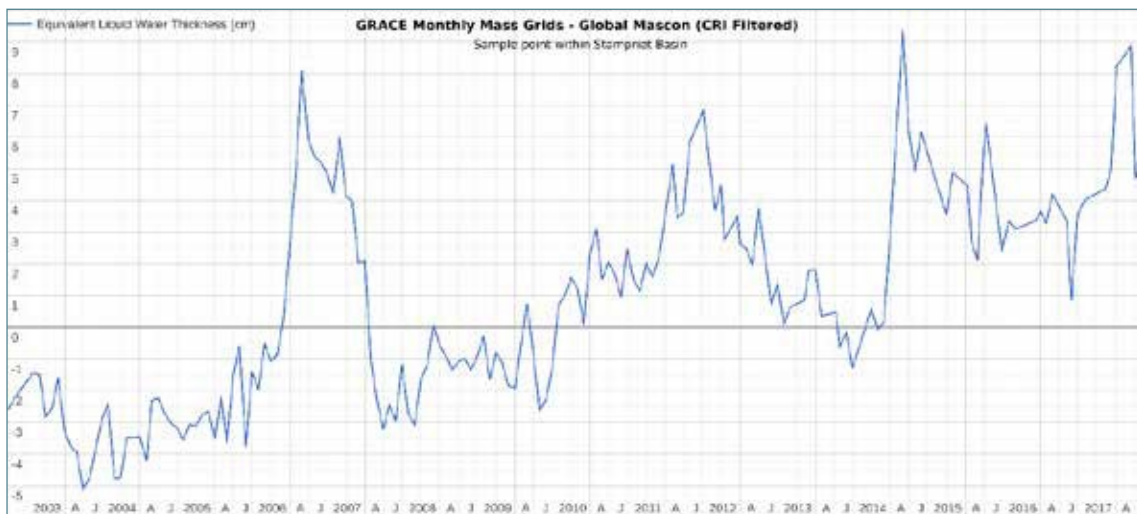
Potential Evapotranspiration (PET) is the main driving force moving water out of the STAS. It is used as an input variable by the UZF package to calculate real evapotranspiration from the unsaturated zone and from the water-table. Here we sourced PET estimates from NASA Global Land Data Assimilation System (GLDAS) (Beaudoin and Rodell, 2019).

Since 2002, the GRACE missions I and II (Follow-on) have been providing the first observations of total water storage (TWS) at a global scale. These missions have been extremely useful in particular with regards to our knowledge of the water cycle and climate change. In arid regions such as the STAS,

GRACE TWS data correspond to storage variations in the saturated and unsaturated zones. Our integrated hydrological model of the STAS also simulates saturated (MODFLOW) and unsaturated (UZFI) storage. So here, the GRACE data are not required as an input for

the model, instead they will provide, at a later stage, independent observations with which to compare water storage simulated by the model. As observed in Figure 2, GRACE data show a significant increase in TWS over the STAS from 2003 to 2017.

Fig. 2.
Variation in total water storage (cm water equivalent) over the STAS from 2003 to 2017



(© CSR Mascon release 6) (https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/).

Discussion

The integrated hydrological modelling approach has been useful in furthering our understanding of the STAS in relation to other neighboring aquifer systems (the system boundaries, main aquifers and their extent, regional groundwater flow, resource quantification estimates, among others). In addition, the flexibility of the framework in allowing the use of remotely sensed data to augment the limited data in the area is another important contribution of this study. Although this is important, there remains a need to develop groundwater and hydrological monitoring networks to improve in situ data availability in the area. Overall, the work and findings from this study further demonstrate the importance of science in the overall understanding and management of water resources to inform policy development/direction in an area highly dependent on

groundwater such as the STAS. In future, the proposed model needs to assist with providing answers to the following questions in order to improve water resources management in the STAS area:

What will be the effect of increased pumping in the STAS area when considering possibilities of more water consumption due to mining, for example? There are already new mining activities in the Ghanzi area in Botswana.

- How can the model be used to evaluate the effects of climate change/variability on groundwater recharge/discharge in the STAS area?
- What (and how much) does it take to maintain the model so as to derive maximum benefit with the management of groundwater in the area?

- The GGRETA project started in 2014 and addresses issues related to transboundary aquifers and responds to the pressing need to increase knowledge about their physical and socio-economic characteristics. GGRETA forms a part of the UNESCO's International Hydrological Program (IHP), the International Shared Aquifer Resources Management Initiative (ISARM) and the Transboundary Water Assessment Program (TWAP).

On the last account, 72 TBAs have been identified in Africa (40% of the continent). The mapping of these TBAs is regularly updated (Nijsten et al., 2018) and the difficulty encountered here to establish the STAS boundaries is a clear reminder of the need for this mapping program to continue.

Scaling up of the approach developed for the case study of the Stampriet to other TBAs is possible. In particular, we found the application of remote sensing to model groundwater very useful. As more and more remote sensing data become readily available this method could easily be extended to other regions.

This study also highlights the complexity of the STAS and the many aspects that need to be taken into account for its study and management. Though useful for comparison across TBAs, this complexity serves as a warning about the dangers in summarizing such a system into a series of simple indicators.

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Hydrogeological conditions on the border between Serbia and Bulgaria to assess the transboundary groundwater transfer

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Abstract

Serbia and Bulgaria have a common state border of about 360 km. The aim of the present study is to analyze the boundary groundwater bodies in the two countries and to determine the probability of groundwater transfer. The groundwater bodies are defined separately in both countries - on the territory of Bulgaria, they are 11, and on Serbia there are 14 included in UNECE evaluation made in 2008. The first step of the present study is to clarify the factors influencing the formation and movement of groundwater. Geological conditions predetermine the presence of different types of groundwater. Along the state border the most widespread are the fractured aquifers' water, formed mainly in the weathering zones of magmatic, metamorphic, and sedimentary terrigenous and terrigenous-carbonate rocks - about 78% of the total length of the border. Different types of aquifer systems with porous media have been identified. The typical karst aquifers have a relatively small distribution along the surveyed border area. Sarmatian sediments form a layered complex, with well-defined aquifers in it, attached to sands and detrital limestones in the northernmost parts of the border. The analysis of the factors proves that during most of the border between Bulgaria and Serbia the probability of cross-border transmission is insignificant. There is a possibility for such a transfer only for the karst basins and for the Sarmatian complex.

Keywords: groundwater, Serbia, Bulgaria.

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