Water balance assessment for the Olifant Sand Water Scheme in Polokwane, South Africa

Internship report 12 – 26 November 2019

Introduction

Water resources in the semi-arid Limpopo basin are stressed due to the intensive water use in the irrigated agriculture and growing cities (Cullis et al. 2011; Zhu, et al. 2012). The natural renewable water availability is highly seasonal and precipitation falls mainly in the summer months (October-April). Streams are therefore often ephemeral streams and cannot sustain the continuous water demand of urban and agricultural water users. Those water users often complement the natural water availability with water from surface water reservoirs and groundwater (Cullis et al. 2011). In Polokwane, an economic hub in the South African Limpopo basin, urban water demand is met by importing large volumes of surface water from surrounding reservoirs (Haupt et al. 2018; Polokwane Municipality 2018). During periods of peak demand, i.e. during droughts, groundwater is used intensively to complement shortages in surface water (Murray 2004 ; Cullis et al. 2011). Outside the city boundaries of Polokwane, groundwater is largely used to sustain the irrigated agriculture located east of the ephemeral Sand river. The aquifer consists of a 20 m thick alluvium layer, which is connected to the deeper weathered granite-gneiss rocks. Groundwater abstractions yield water from the deeper fractured hard-rock aquifer (Murray & Tredoux 2004 Haupt et al. 2012).

Downstream from Polokwane, groundwater is recharged by a Managed Aquifer Recharge (MAR) scheme that discharges treated wastewater into the ephemeral Sand river (Haupt et al. 2018). A similar setup is used in Seshego and Mangwenk wastewater treatment plant, which also recharge treated wastewater of Polokwane and Mangwenk using a mostly dry streambed (Figure 1). In theory, the recharged MAR water would be beneficial for the agricultural water users downstream of Polokwane. However, to-date studies have focused on the wastewater treatment plant in Polokwane (Theagarajah, 2019) or on the water availability in the Hout catchment, which is a sub-catchment of the Sand catchment (Ebrahim, et al. 2019). Hence, the impact of the MAR scheme on water resource availability remains unknown.

This study is a first exploration of water balance components in the Polokwane region. For this region, the Olifant Sand Water Scheme (OSWS) is used as a relevant water management unit. First, the incoming water sources are identified and described. These include both natural water balance components (precipitation), external import of water, and the impact of the MAR system on the water balance for the unit. Water is leaving the OSWS via evapotranspiration, runoff, export of water and groundwater use. One average annual water balance is presented using all these components in a schematic overview.

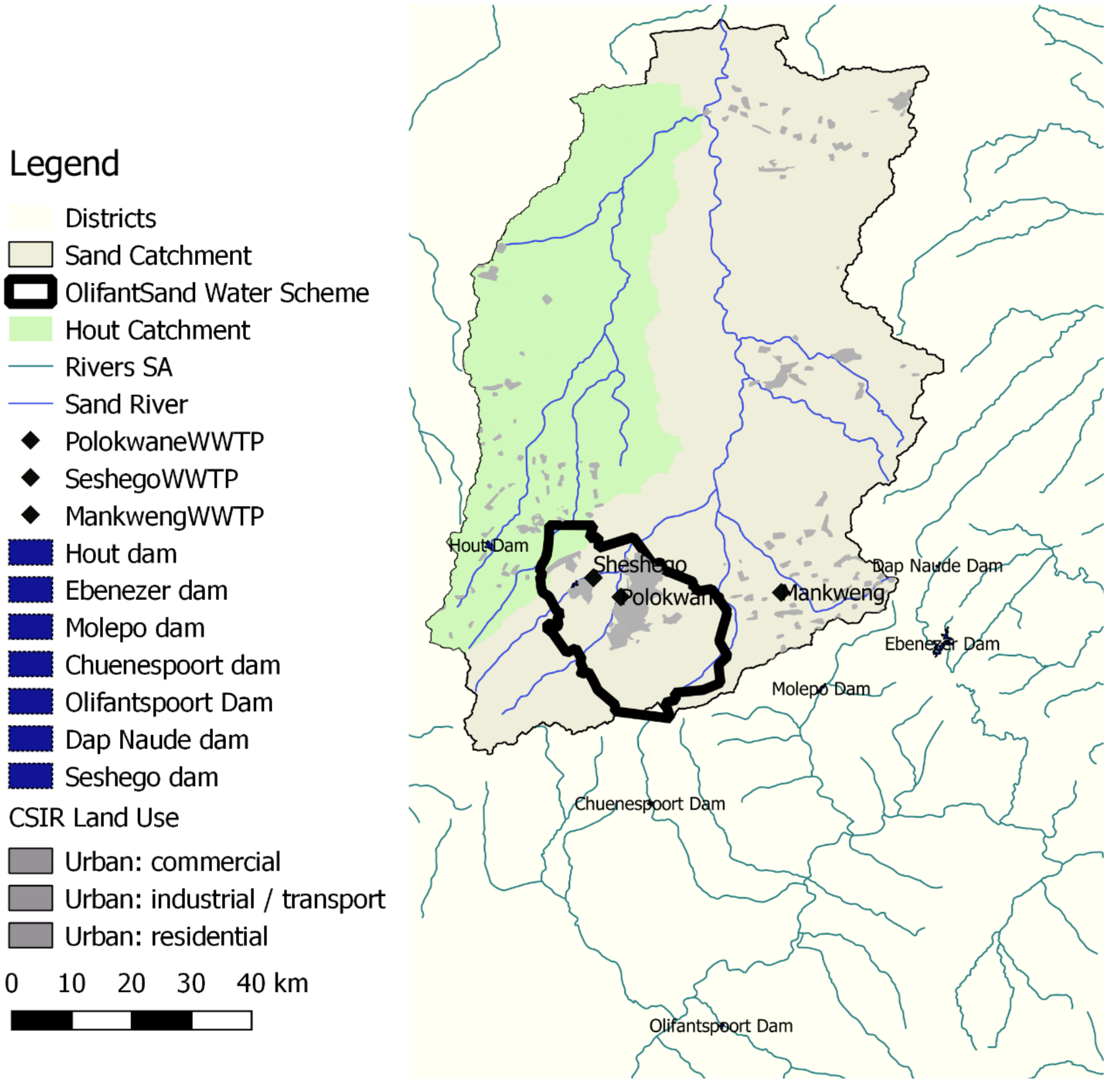

Figure 1: Olifant Sand Water Scheme in the Sand catchment (part of Limpopo basin). The three wastewater plants are shown (black diamonds), the sand river (blue), reservoirs that supply water to the water scheme and the main urban areas.

Data and Method

Precipitation and climate data were obtained of the South African Weather Service (SAWS) that has a 20 year observation record in Polokwane weather station. The record contained daily observations of precipitation, temperature (min/max), humidity, pressure, wind speed, and wind direction. Precipitation time series were aggregated to annual averages to indicate a long-term average based on the observations from 1993 to 2014. The reference evapotranspiration was computed using the Hargreaves-Samani method in the SPEI package using the monthly minimum and maximum temperature (Hargreaves & Samani 1985; Moeletsi et al. 2013; Beguería 2017). This reference evapotranspiration (computed for grass as a reference crop) was converted into potential evapotranspiration for field conditions using a the same approach as Ebrahim et al. (2019), who analysed water availability in the Hout catchment. The potential evapotranspiration for field conditions was calculated using crop factors as computed by Ebrahim, et al. (2019) for fallow land, urban area and irrigated area.

In the OSWS, natural surface water is discharging by the ephemeral Sand River. Streamflow data were estimated using the rainfall-runoff model of Ebrahim, et al. (2019), focusing on the sub-catchment, as there is no intermediate gauging station available. In addition to the natural discharge, large amounts of surface water are imported from reservoirs nearby to sustain the urban water demand. Annual average imported volumes were taken from the work of Haupt et al. (2018). Haupt et al. (2018) also reported the amount of additional recharge and discharge of the urban wastewater.

The last component of the water balance is groundwater storage that is changed according to groundwater usage (extraction) and groundwater recharge by the MAR scheme. The study of Haupt et al. (2018) published annual average groundwater use for Polokwane, which is givinguses the amount of registered water use per water user. These registered amounts indicate the official water use (by the given licence), which might be exceeded by users in the catchment. Actual records of water abstraction are unavailable, leaving these registered volumes of groundwater use as a best estimate. The amount of recharged water was obtained from the discharge of the wastewater treatment plans.

The water balance was calculated using annual average data for the available datasets. The time series of the water balance components varied. A 20-year observation record was available for precipitation and temperature data, compared to 3 complete years of discharge data. For groundwater recharge and usage, only a long-term average was reported by Haupt et al. (2018). Hence, no annual water balance could be computed. Changes in groundwater storage were not included in this water balance, only the explicit inflow and outflow of groundwater were used.

Results

The OSWS includes Polokwane city and the surrounding agricultural lands (Figure 3). The total area of the OSWS is 791 km^2. The water balance of the water scheme consists of the natural water balance, which is altered by water use in urban areas in Polokwane and the irrigated areas. The additional water import and recharged MAR water are also included in the water balance. Figure 5 shows an overview of all water balance components, with averaged annual estimates for each component. These are explained in detail in the following paragraphs.

Precipitation

In Figure 2, the average annual precipitation in Polokwane weather station is shown that varies from 255 mm/y (2002) to 869 mm/y (1996). The long-term average is 482 mm/y (blue dotted line in Figure 3), which equals 381.3 Mm^3/y for the Olifant Sand water scheme area.

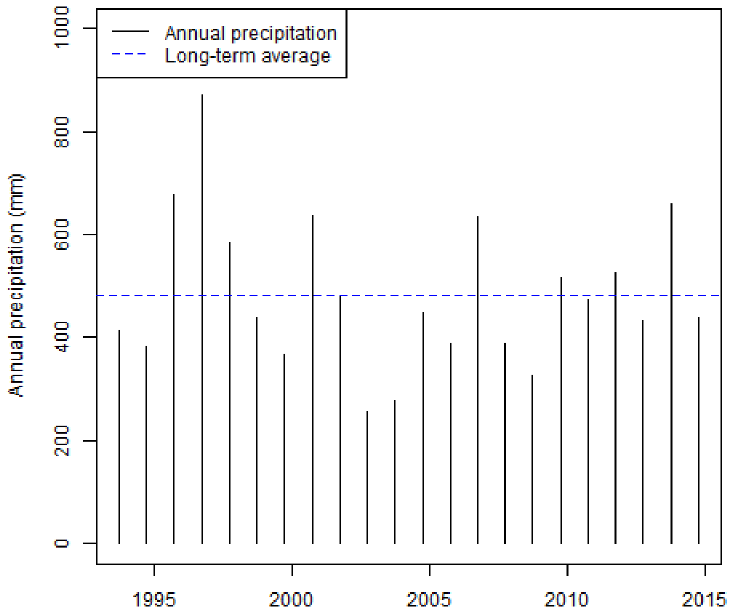

Figure 2: Annual precipitation measured in Polokwane weather station. The long-term mean (dotted blue line) is computed using the available complete years (n=21) of daily precipitation (1993-2014).

Imported surface water

Imported surface water comes from seven nearby surface water dams indicated in Figure 1. The long-term average is indicated in Table 1 that presents the total amount of imported water (22.3 Mm^3/y). Note that allocated volumes are higher than the delivered volumes for all dams. Less water delivered could be due to lower water availability or over-allocation of water rights (Ebenezer, Olifantspoort) and infrastructural constrains (Dap Naude and Ebenezer) (Haupt et al. 2018). Detailed time series of water imports of Ebenezer show that the supplied volumes are highly variable. In the time period 1990-2000, average supplied volumes of Ebenezer were around 5.4 (Mm^3/y) with exceptionally low volumes in 1994, 1995 and 2000.

Table 1: Long-term annual average volumes of surface water import to OSWS. Volumes are converted from kl/d to Mm^3/y from the work of Haupt et al. (2018).

Surface water dam		**Allocated water (Mm^3/y)**	**Delivered volumes (Mm^3/y)**
Large dams	Ebenezer	12	7.9
	Dap Naude	6.5	4.6
	Olifantspoort	32.5	9.5
Small dams	Chuenespoort	2.7	0
	Molepo	2.2	0
	Hout River	3.4	0
	Seshego	2	0.3
	Total	**61.3**	**22.3**

Recharged water

The last source of incoming water is the recharged treated wastewater from the wastewater treatment plants. Two wastewater treatment plants are located within the Olifant Sand water scheme. These plants discharge generate a total of 17.2Mm^3/y each year (see Table 2). Part of this treated wastewater is exported and the remainder is released into an ephemeral Sand river.

However, the continuous release of treated wastewater changes the ephemeral stream into a perennial stream, starting from the wastewater plants. Due to a saturated streambed and the constant release of water, not all treated wastewater infiltrates immediately. Haupt, et al. (2018) estimated using an empirical relationship that with a flow of 3.6Mm^3/y all water would be infiltrated within the Olifants Sand catchment. The infiltration rate reduces exponentially given the generated effluent and based on this work 50% of the flow in Polokwane infiltrates within the water scheme and 100% of the flow in Seshego. The estimated infiltrated wastewater is therefore 6.5Mm^3/y. The remainder of discharge is assumed to infiltrate further along the streambed in the Sand catchment.

Table 2: Overview of flow divisions from two wastewater treatment schemes in OSWS. The columns indicate the proportion of generated effluent (1), of which an amount is exported (2), released into the streambed (3), and of the latter, an amount is infiltrated within OSWS (4) or discharged further into the Sand catchment (5).

Wastewater treatment plant	Effluent generated (Mm^3/y)	Exported water (Mm^3/y)	Released treated wastewater (Mm^3/y)	Estimated infiltration (Mm^3/y)	Discharge (Mm^3/y)
Polokwane	11.0	5.1*	5.9	2.9	**2.9**
Seshego	6.2	2.6	3.6	3.6	**0**
Total	**17.2**	**7.7**	**9.5**	**6.5**	**2.9**

*Export of wastewater to mining industry outside OSWS catchment

Evapotranspiration

The annual reference evapotranspiration is 2090 mm/y, which is in the same order of magnitude as pan evapotranspiration as reported by Lombaard et al. (2015). This reference evapotranspiration was converted into potential evapotranspiration according to the land use and the associated crop factor of this land use (based on the work of Ebrahim et al. (2019)). In Figure 3, urban, irrigated, and fallow land in the OSWS are shown, which are also summarised in Table 3. These estimates for the potential evapotranspiration do not represent the actual evapotranspiration, which is moisture limited in the semi-arid areas. Given the current data and time restrictions, it is not feasible to obtain these for the Olifant Sand water scheme. An alternative approach is to use the estimates of Ebrahim, et al. (2019), who used two different models (PRMS and MODFLOW) to estimate the actual evapotranspiration for the Hout catchment. These estimates are in the order of 305.2 mm/y and 394 mm/y and are therefore deemed better estimates than the potential evapotranspiration. In the current water balance for the OSWS, the mean of these modelled estimates of actual evapotranspiration is used that is 276.6 Mm^3/y. Options to improve these estimates are discussed in the Discussion.

Table 3: Computation of reference and potential evapotranspiration for different land use categories in the Olifant Sand water scheme

Land use	Area (km^2)	Crop factor as applied in Ebrahim et al. (2019)	Potential evapotranspiration (mm/y)	Potential evapotranspiration (Mm^3/y)
Urban	136.6	0.1	209	28.6
Irrigated land	87.0	0.7	1463	127.3
Fallow	702.6	1.2	2508	1762.1
Total	**791**	**-**	-	1918.0

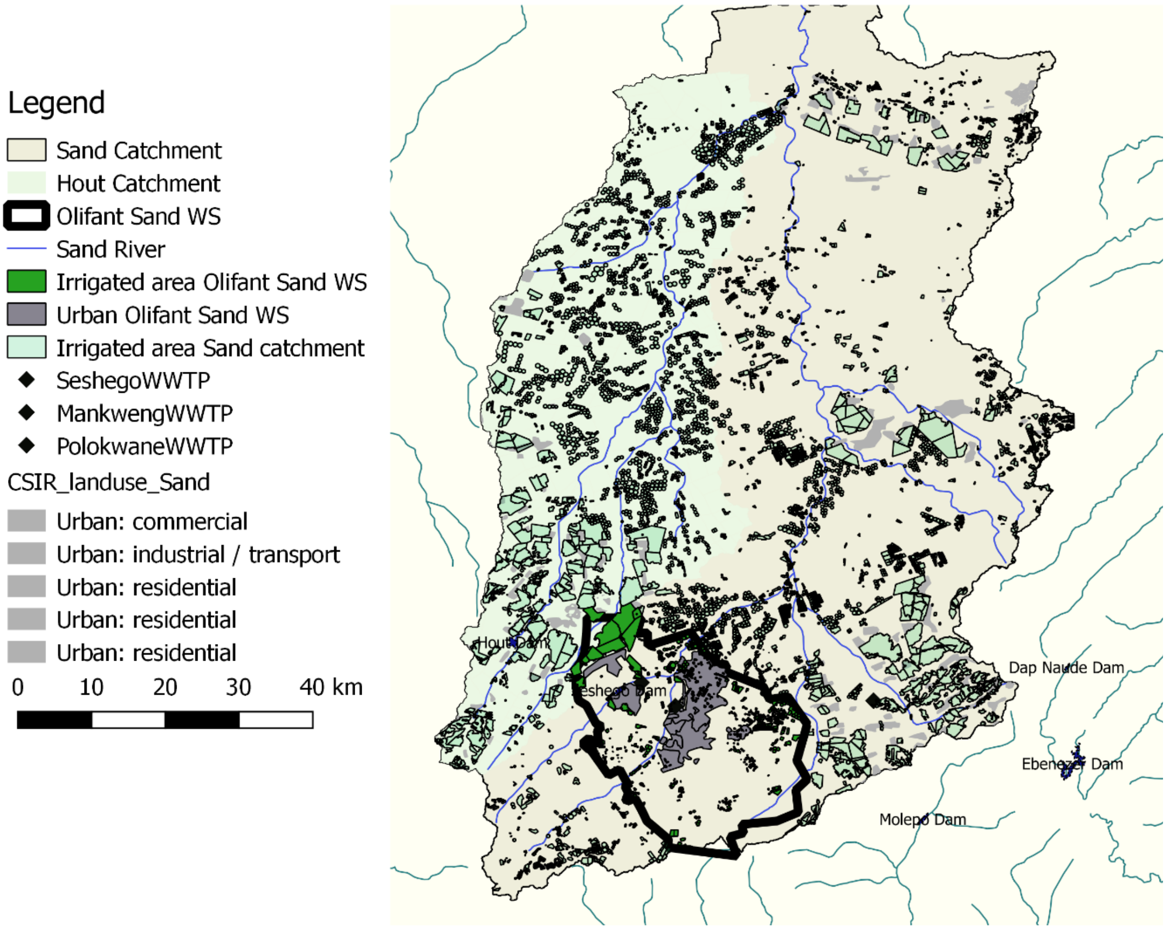

Figure 3: Land use map of Sand catchment showing the irrigated and urban areas in the Olifant Sand water scheme (brighter grey and green colours) and irrigated and urban areas in the Sand catchment (paler green and grey colours).

Runoff

The runoff from the OSWS is a composition of the discharged treated wastewater and the natural runoff. As discussed above, the discharge from Polokwane and Seshego wastewater treatment plant is estimated at 2.9 Mm^3/y (Table 2). The natural runoff is determined using the rainfall-runoff model PRMS, as calibrated by Ebrahim et al. (2019). OSWS falls in two hydrological response units (HRU 54 and 51, see SI of Ebrahim et al. (2019)). In Figure 4, the modelled runoff is shown for the combined modelled discharge of the water scheme. In the short time series (2003-2007), the flow pattern of the ephemeral stream is clearly identified, following the wet and dry season of the monthly precipitation as measured in Polokwane weather station. On average, the natural discharge is estimated at 0.15 Mm^3/y, which is based on PRMS modelled data for all complete years in the time series (2004-2007). The combined discharge of the wastewater treatment plants and the natural surface runoff is therefore deemed at an average of 3.1 Mm^3/y.

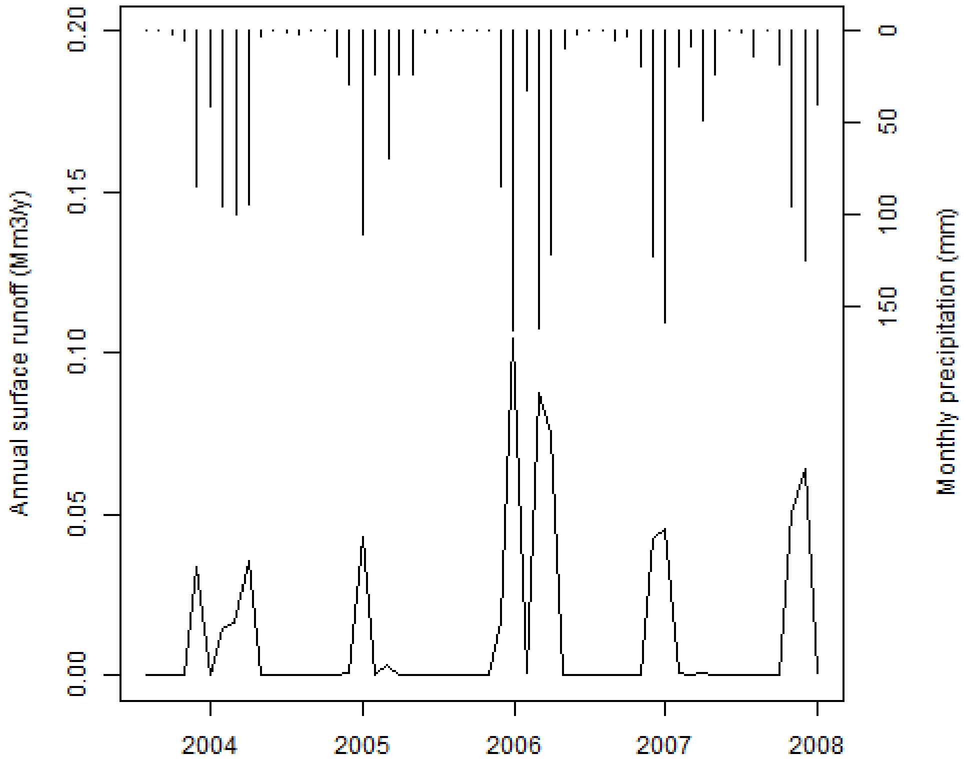

Figure 4: Modelled discharge using PRMS for two HRUs that cover the Olifant Sand water scheme. The calibrated model of Ebrahim et al. (2019) is used to extract the data for the two HRUs. Monthly precipitation records from Polokwane weather station are shown on the second Y-axis.

Groundwater use

Groundwater use is allocated and registered for domestic, agricultural, and industrial water use. The reported volumes of Haupt, et al. (2018) give an indication of recent groundwater allocations in the Olifant Sand water scheme (Table 4). These registered volumes are seen as a best estimate given the unavailable groundwater abstraction records or actual current abstraction rates. Based on these water allocations, the total groundwater use is estimated on 4.2 Mm^3/y.

Table 4: Groundwater allocations in Olifant Sand water scheme

Water users	Groundwater use (Mm^3/y)
Households	1.34
Irrigation	1.40
Livestock	0.15
Industry	1.27
Total	**4.2**

Exported water

The last outgoing source is the amount of exported water from the wastewater treatment plants. This water is reused by industry and agriculture located outside the OSWS. In total, an amount of 7.7 Mm^3/y is currently exported from the water scheme (Table 2).

Water balance

A schematic overview of the water balance for the OSWS is shown in Figure 5. The incoming sources of water are precipitation (381.3 Mm^3/y) and imported surface water (22.3 Mm^3/y). Water leaves the system via evapotranspiration (276.6 Mm^3/y), runoff (3.1 Mm^3/y) and exported water (7.7 Mm^3/y). This first estimate results in a positive water balance of 116.2 Mm^3/y. However, there are substantial uncertainties associated with some of these estimates, which are coloured in red (evapotranspiration, runoff, and groundwater use). The uncertainty of these water balance components is further discussed in the Discussion.

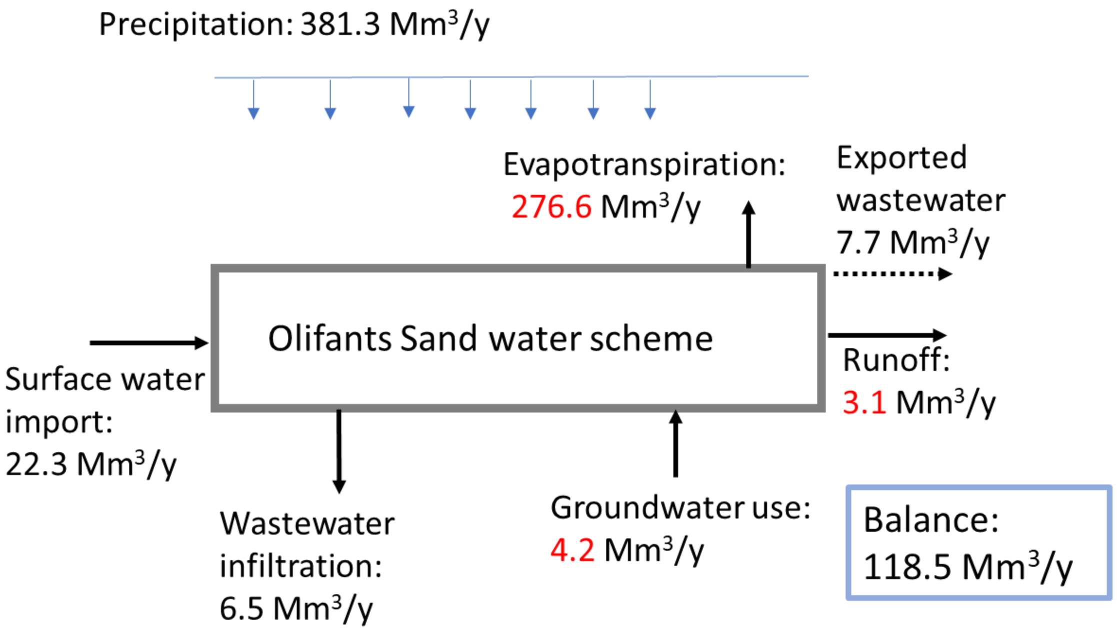

Figure 5: Schematic overview of water balance components with estimated annual amounts for the Olifant Sand water scheme. The Balance indicates?

Discussion and Conclusion

This first water balance assessment contains some large uncertainties regarding the evapotranspiration and surface runoff. For example, the estimated evapotranspiration is based on two models that are calibrated for the Hout catchment. These models are using computed reference evapotranspiration and (dynamic) crop factors depending on the land use to estimate the potential evapotranspiration. The first uncertainty in the estimate of evapotranspiration is associated with the different proportion of irrigated, urban, and fallow area. For example, the proportion of irrigated land is 11% in OSWS compared to 0.8% in the Hout catchment (Ebrahim et al. 2019). This could increase the evapotranspiration, as a larger area in the water scheme is irrigated continuously. The urban area is also larger, which potentially would reduce the evapotranspiration. In other words, the change in potential evapotranspiration will also result in a different soil moisture balance that changes the computation of the actual evapotranspiration. It is expected that given the larger proportion of irrigated area the current estimate of evapotranspiration is too low. It remains uncertain how this estimate changes for a larger proportion of urban area. Therefore, it is recommended to improve the current estimate of the actual evapotranspiration before adopting these results in further applications.

Additional uncertainties are associated with the computed runoff. The runoff is a composite of reported discharges from wastewater treatment plants and modelled natural runoff. It is possible that there is an additional source of runoff, namely unreported or untreated wastewater that is discharged into the Sand River. The amount of *reported treated wastewater* represents only 56% of the imported surface water and groundwater allocations. The remaining water could be consumed by water users, in particular by industrial water users. However, without information about registered water use and water consumption it remains uncertain if the water consumption represents indeed 56?% of the water use. Hence, it is recommended to further investigate registered water use and water consumption to make a more accurate estimate of treated and untreated wastewater.

Groundwater allocations are seen as another source of a potentially large uncertainty. These allocated groundwater abstractions are reported as part of the groundwater abstraction licence. The volumes should therefore represent the maximum groundwater abstraction. However, unlicensed groundwater use is common and licenced amount might be exceeded during periods of water shortage, or during droughts (Collis, et al. 2011). This implies that the actual groundwater use is potentially larger and included in the analysis.

Potential smaller uncertainties are included in the estimated recharge of the treated wastewater by Haupt, et al. (2018). The empirical relationship used for the infiltration of wastewater in the streambed might change over time or due to increased groundwater use. More in-situ testing in the streambed would be required to determine the uncertainty of this estimate.

Given the short and sporadic timescales of the imported surface water, it is possible that the averages of imported surface water do not include the long-term variability in climate. This could be investigated using long-term precipitation and reservoir levels time series. However, in absence of these continuous time series, the average volumes as reported in the work of Haupt, et al. (2018) are the best available estimate to date. Given the large variability and number of low water availability in the reservoirs, it can be expected that the indicated averages might overestimate current deliveries.

The overall water balance is positive, implying an accumulation of water within the OSWS. We have not looked at groundwater levels in this study, so we have no idea of possible storage changes in the groundwater, or of lateral fluxes of groundwater out of, or into, the area, and this could present an unaccounted for factor explaining some of the excess in the water balance. This is an unexpected finding, as the Polokwane municipality (2018) reported a shortage of water given a higher peak demand. This water balance assessment, however, only considers average conditions and does not account for an increased demand due to water shortage or drought conditions. In the work of Haupt, et al. (2018), a slightly negative balance is shown for the OSWS, based on a higher current demand that exceeds the licenced groundwater use. These two reports (Haupt, et al. 2018 and Polokwane municipality, 2018) suggest that this first water balance assessment might underestimate the current water use, and therefore shows a more optimistic water balance. This hypothesis is supported by results of Cullis et al. (2011) and Zhu et al. (2012), who both found increasingly stressed water resources in Limpopo basin. Even though this water balance assessment can be seen as a useful first exploration, further research is strongly recommended to address the uncertainty components mentioned.

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