

Potential water supply of a small reservoir and alluvial aquifer system in southern Zimbabwe

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Abstract

Groundwater use by accessing alluvial aquifers of non-perennial rivers can be an important additional water resource in the semi-arid region of southern Zimbabwe. The research objective of the study was to calculate the potential water supply for the upper-Mnyabezi catchment under current conditions and after implementation of two storage capacity measures. These measures are heightening the spillway of the 'Mnyabezi 27' dam and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River. The upper-Mnyabezi catchment covers approximately 22 km² and is a tributary of the Thuli River in southern Zimbabwe. Three coupled models are used to simulate the hydrological processes in the Mnyabezi catchment. The first is a rainfall-runoff model, based on the SCS-method. The second is a spreadsheet-based model of the water balance of the reservoir. The third is the finite difference groundwater model MODFLOW used to simulate the water balance of the alluvial aquifer. The potential water supply in the Mnyabezi catchment under current conditions ranges from 2,107 m³ (5.7 months) in a dry year to 3,162 m³ (8.7 months) in a wet year. The maximum period of water supply after implementation of the storage capacity measures in a dry year is 2,776 m³ (8.4 months) and in a wet year the amount is 3,617 m³ (10.8 months). The sand storage dam can only be used as an additional water resource, because the storage capacity of the alluvial aquifer is small. However, when an ephemeral river is underlain by a larger alluvial aquifer, a sand storage dam is a promising way of water supply for smallholder farmers in southern Zimbabwe.

1. Introduction

Access to irrigation water for smallholder farmers is limited in the Limpopo basin (Love *et al.*, 2006). In the semi-arid regions of Zimbabwe, artificial surface reservoirs have been designed to meet the domestic and agricultural (mainly livestock) water requirements of smallholder farmers in dry periods. However, most of the smaller reservoirs dry out within half a year after the main rainy season. In this situation, groundwater use by accessing alluvial aquifers of non-perennial rivers can be an important additional water resource (Dahlin and Owen, 2005; Moyce *et al.*, 2006). Barker and Molle (2004) describe an

alluvial aquifer as a groundwater unit, generally unconfined, hosted in laterally discontinuous layers of sand, silt and clay and deposited by a river in a river channel, banks or flood plain. Alluvial aquifers in large perennial rivers already meet agricultural and domestic water requirements in some cases in southern Africa (Seely *et al.*, 2003; Love *et al.*, 2007). The groundwater storage of alluvial aquifers of these large rivers has a large potential water supply (Owen and Dahlin, 2005; Moyce *et al.*, 2006). However, most smallholder farmers in semi-arid regions live near to smaller non-perennial rivers that make research to groundwater resources in these smaller alluvial aquifers interesting.

This study concentrates on the hydrological processes occurring in the upper-Mnyabezi catchment, which is a tributary of the Thuli River in southern Zimbabwe. Water is stored in the reservoir of the ‘Mnyabezi 27’ dam and in the alluvial aquifer of the Mnyabezi River. These two ways of water storage ensure water availability during the dry season for plants, animals and people, but is still not enough to supply water the whole year round. The research objective is to calculate the potential water supply for the upper-Mnyabezi catchment in the semi-arid region of southern Zimbabwe for current conditions and after implementation of two possible storage capacity interventions. These measures are (i) heightening the spillway of the ‘Mnyabezi 27’ dam and (ii) constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River. Sand storage dams store water in the alluvial sediments, which are accumulated upstream of the dam (Hanson, 1987; Mansell and Hussey, 2005). The sediment becomes saturated after a river flow event.

2. Study area

The river upstream of the ‘Mnyabezi 27’ dam is about 8 km long and the catchment area covers approximately 22 km². The study area also includes the alluvial aquifer for a length of 1.0 km downstream of the dam. The soil of the Mnyabezi catchment area consists of sandy loam and the underlying layer consists of weathered granite (Matura *et al.*, 2007). The soil layer is shallow to moderately deep and is on average 0.5 m thick (Moyo, 2001). The land use is a mixture of agricultural fields (4.0 %), farmsteads (0.5 %) and sparsely wooded degraded rangeland (95.5 %) where cattle graze.

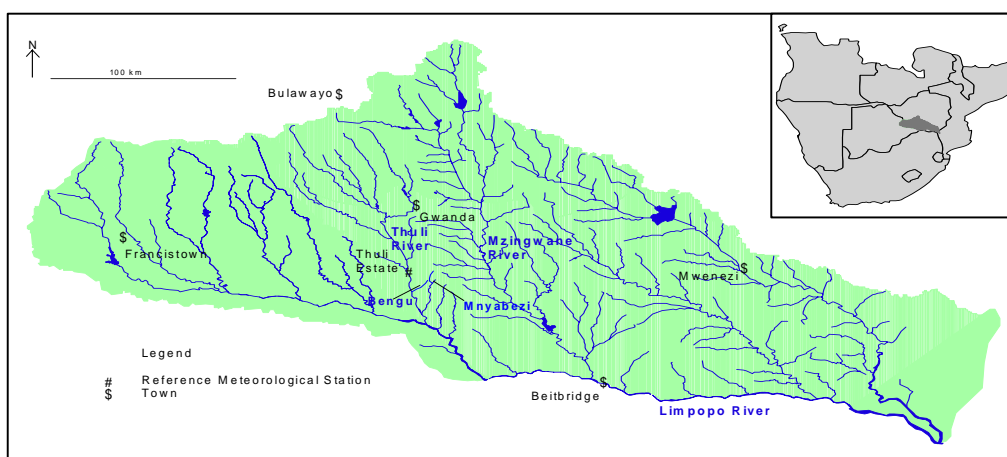


Figure 1: Location of Mnyabezi River in the northern Limpopo Basin. Inset: location in southern Africa.

The main use of the highly silted reservoir is for drinking by cattle. The local community is planning to build a new spillway. The difference between the bottom of the reservoir and the top of the spillway is 0.73 m (for the new spillway it is 1.00 m). When the reservoir is full, it covers an area of 1.54 ha and reaches a total volume of 5,600 m³. Every year the reservoir dries out during the dry period of the year. The Mnyabezi River is highly ephemeral, which means it only flows during and shortly after a heavy rain event. The alluvial aquifer downstream of the dam has a width varying from 9 - 11 m, a maximum depth of 1.4 m and a slope of 0.28 %. Physical probing done during field visits indicate some locally thin clay layers at several depths, but the main material is fine to medium sand (hydraulic conductivity; $k \approx 69 \text{ m day}^{-1}$).

3. Methods

This paragraph explains the methods used in the study. The first describes the field measurements done during the March – May 2007. The second sub-paragraph elaborates on the modelling of the hydrological conditions in the Mnyabezi catchment for a dry, normal and wet year. The last sub-paragraph describes the calibration method using the measured data.

3.1 Field measurements

Alluvial aquifers in the arid regions recharge relatively fast compared to areas with moderate meteorological conditions (Gorgens and Boroto, 1997; Moyce *et al.*, 2006). These short hydrological processes require a daily time step for the modeling process, which in turn requires daily input data. Hydrological variables (like precipitation, evaporation, water abstractions of cattle, water level in the reservoir and the water table in the alluvial aquifer) were measured daily between March - May 2007. Several hydro(geo)logical parameters (like hydraulic conductivity, hydrological soil group, land use, land treatment, dimensions of the reservoir and the profile of the alluvial aquifer) were measured on a once-off basis.

3.2 Modeling

In this study, three coupled models have been used to simulate the hydrological processes in the Mnyabezi catchment (figure 2 visualizes the flows between the models). Every year the variability of rainfall events and the amount of rainfall differs. Consequently, the potential water supply differs for each year. The aim of the study is to calculate the potential water supply during a typical dry, normal and a wet year. Surface and groundwater runoff in the study area have been simulated for these three typical years, where a year starts at the beginning of the main rainy season (1st of November) and ends at the end of the dry season (31st of October). Three typical years have been selected from the daily rainfall records of the Thuli Estate meteorological station between 1987 and 2000. Note that in (semi-)arid regions, the variability of rainfall events during a year mainly determines if a year will be typified as dry, normal or wet in water supply terms (Butterworth *et al.*, 1999). A typical dry year was '88/'89 (259.2 mm), a normal year was '97/'98 (331.9 mm) and wet year was '96/'97 (568.4 mm).

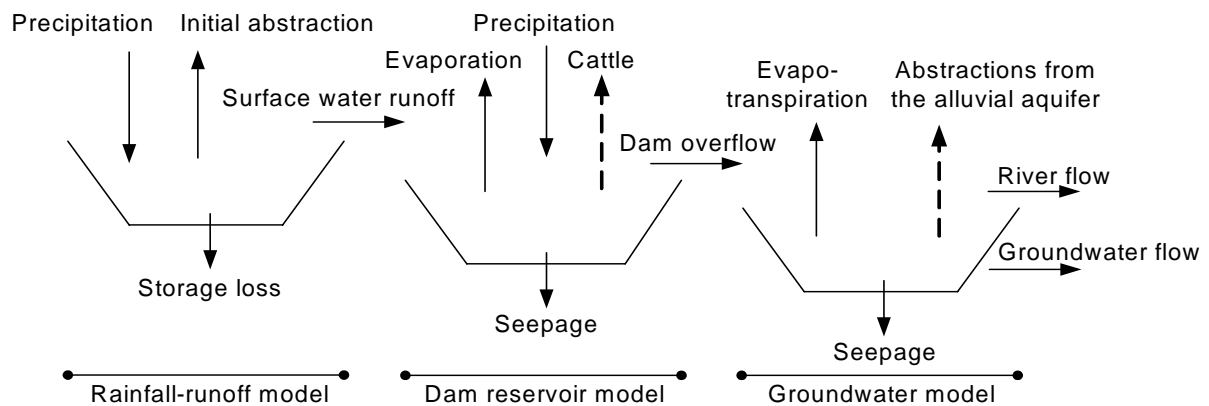


Figure 2: Schematization of flows between hydrological models; the dashed lines represent the potential water supply

A simple rainfall-runoff model, based on the SCS-method (USDA-SCS, 1972; 1986), has been used to calculate the surface water runoff caused by precipitation. The method relates the discharge (Q) to total rainfall (P) and storage capacity via an empirical relation. The method is discussed further elsewhere (De Hamer *et al.*, 2007).

A spreadsheet-based reservoir model has been used to simulate the water level in the artificial surface reservoir of the 'Mnyabezi 27' dam. The runoff from the Mnyabezi catchment, calculated by the rainfall-runoff model, forms the inflow variable for the reservoir model. The model also incorporates the variables (i) direct recharge by precipitation, (ii) open water evaporation (iii) abstraction by cattle and (iv) seepage. Groundwater flow in these semi-arid regions into the reservoir is usually negligible (Barnes, 1994; Sandstrom, 1997). The potential water supply of the reservoir is the summation of the daily amount of water that cattle can consume from the reservoir. Dam overflow occurs when the water level in the reservoir is higher than the height of the spillway. We have simulated the water level and the potential water supply under current conditions and under the scenario with a heightened spillway.

The finite difference groundwater model MODFLOW (McDonald and Harbaugh 1988; Harbaugh, 2005) has been used to simulate daily groundwater levels in the alluvial aquifer downstream of the dam. The model consists of three layers; a top layer (0.7 m) representing the soil, a second layer representing the alluvial aquifer and a third layer representing the underlying granite layer. The general model domain is 230 m in width and 1,000 m in length with a horizontal resolution of 5x5 m. Because the main hydrogeological processes occur in the alluvial aquifer and adjacent river banks, these areas have a higher resolution of 2x5 m. The alluvial aquifer is modelled as a rectangular shape with a depth of 0.9 m, a width of 10 m and a slope of 0.28 %. In the MODFLOW model, hydrogeological characteristics, like hydraulic conductivity, specific yield and porosity, have to be assigned to every layer separately. Due to the loose structure of the alluvial material, the hydrogeological parameters have been assumed constant in all directions. This is not true for granite due to its complex rock structure. In the Mnyabezi catchment, the granites are altered and best described as weathered older gneisses (Matura *et al.*, 2007). Normally, fresh granite has a very low primary porosity, but granite always has a secondary porosity due to weathering and an interconnected system of fractures, fissures and joints, which allows the flow and

storage of groundwater (Todd, 1980). Due to this secondary porosity the hydraulic conductivity, porosity and specific yield of granite are non-homogeneous. Nevertheless, MODFLOW calculates with average values. We have simulated the water balance and the potential water supply of the alluvial aquifer under current conditions and under scenario of a sand storage dam.

3.3 Calibration

Since the Mnyabezi River is ungauged, it was necessary to calibrate the rainfall-runoff model in combination with the reservoir model. By measuring the increase in water level of the reservoir after a rain event, the amount of river inflow was calculated. This value was used to calibrate the rainfall-runoff model. For the rainfall-runoff model the initial abstraction was used as the fitting parameter for the calibration of the model. The initial abstraction (I_a) is difficult to determine in (semi-)arid regions due to surface crust forming (FAO, 1991) and the variable transmission losses into the alluvial aquifer (Anderson, 1997). These features make the normal assumption: $I_a = 20\%$ of the potential retention (S) not valid (USDA-SCS, 1972). Studies in southern Africa have used percentages of 10 % and less (Schulze *et al.*, 1993; Hranova, 2006). To obtain the best fit, the initial abstraction was changed between 5.0 and 15.0 % of actual retention. The seepage was used as the fitting parameter for the calibration of the reservoir model. The seepage was varied between 0.0 and 1.0 mm·day⁻¹. The efficiency coefficient developed by Nash and Sutcliffe (1970), resulted in a value of 0.99, using an initial abstraction (I_a) of 7.6 % of actual retention and a seepage of 0.0 mm·day⁻¹.

The observed and calculated groundwater levels in the alluvial aquifer have been used to calibrate the MODFLOW model. The groundwater level measurements resulted in a drying period from the alluvial aquifer of 20 days after a dam overflow event. This relatively fast depletion time is caused by heavy weathering conditions of the underlying granite layer. Due to the lack of a good method to determine the values for the hydraulic conductivity, specific yield and effective porosity for weathered granite, these parameters were used as fitting parameters for the calibration of the model. The hydraulic conductivity for weathered granite ranges between 0.5 – 1.4 m·day⁻¹ (Morris and Johnson, 1967; Davis, 1969; Shaw, 1994). The specific yield for weathered granite ranges between 0.01 and 0.05 and the effective porosity ranges between 0.05 and 0.15 (Todd, 1980; Rushton and Weller, 1989). The hydraulic conductivity and the specific yield were manually varied between the above ranges to make a best fit. Since the sensitivity of the porosity in the model was low, this value was assumed constant at a value 0.08. After the manual calibration, the PEST-module (automatic calibration module) of the MODFLOW model fine-tuned the calibration. A correlation coefficient of 0.99 was obtained using a value of 0.55 m·day⁻¹ for the hydraulic conductivity and 0.03 for the specific yield.

4. Results

This paragraph presents the results of the study under the current condition and after the implementation of the water storage measures. The first sub-paragraph describes the potential water supply of the reservoir including the scenario after heightening the spillway. The second paragraph presents the results of the potential water supply of the alluvial aquifer under current conditions and after implementing a sand storage dam.

4.1 Dam reservoir

The reservoir model has been used to analyze the hydrological characteristics of the reservoir during a dry year ('89/'99), a normal year ('97/'98) and a wet year ('96/'97). The water balance results of the reservoir for these three years are presented in figure 3. The results show approximately the same proportions between natural losses; the evaporation loss is 79 %, cattle abstractions count for 21 % and the seepage losses are negligible. Of course, this means that the total amount of evaporation and abstractions by cattle increases for wetter years in comparison to drier years. Based on the model outputs, it is clear that the differences in reservoir inflow are caused by the different rainfall patterns; in drier years, the rainfall is mainly concentrated during a few heavy rain events and in wetter years, the rain events are less heavy, but more frequent and dispersed over a longer period.

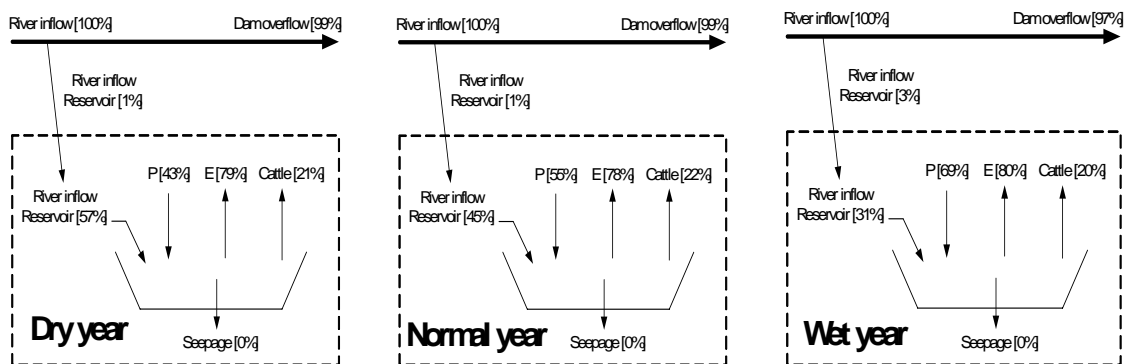


Figure 3: Water balance results of the Mnyabezi reservoir for a dry, normal and wet year

Dam overflow occurs when the water level in the reservoir is higher than the height of the spillway. Figures 4, 5 and 6 show the calculated water levels in the reservoir under the current situation and under the scenario with a heightened spillway. The drying period of the reservoir is approximately 4.5 months (after the last dam overflow event and without rain events during that period). Figures 4 and 5 show that the reservoir stores water for approximately five weeks longer after heightening the spillway to a height of 1.0 m. During the wet year of '96/'97 (figure 6) the increase in drying period is only two weeks, which is caused by the rainfall event in the beginning of April.

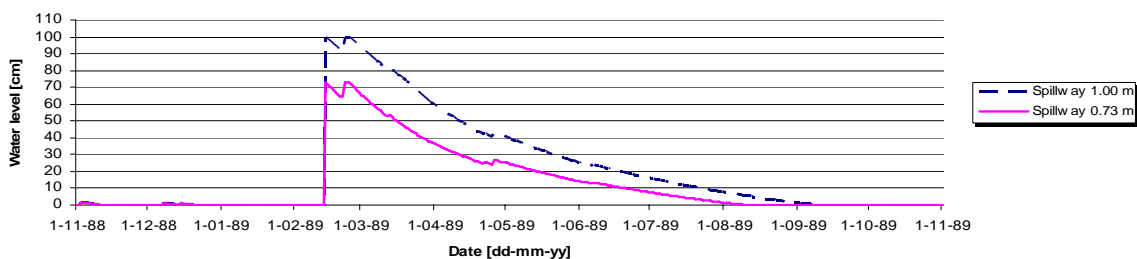


Figure 4: Water level in the Mnyabezi reservoir during the dry year '88/'89

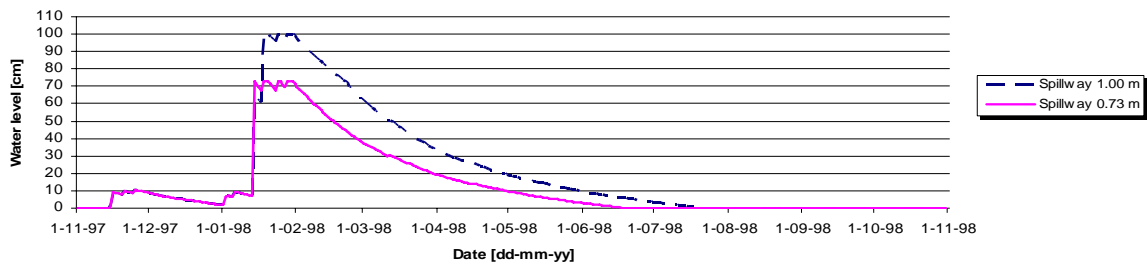


Figure 5: Water level in the Mnyabezi reservoir during the normal year '97/'98

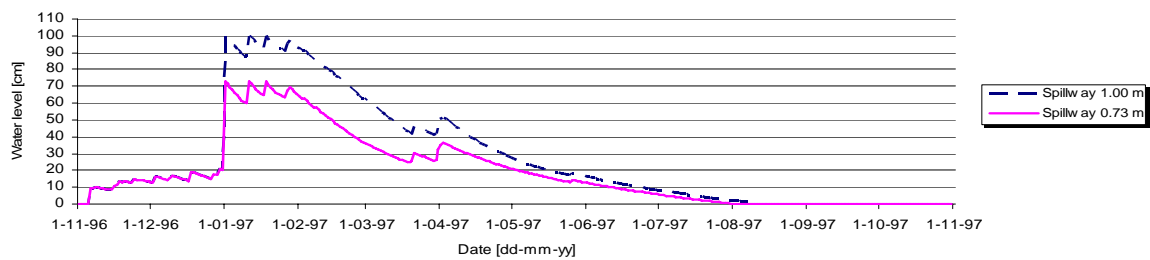


Figure 6: Water level in the Mnyabezi reservoir during the wet year '96/'97

The reservoir model has been used to calculate the amount of potential water supply under the current situation and under the scenario with a heightened spillway (see table 1). The potential water supply is the summation of the amount of water that cattle consume in days when the reservoir contains water. The period of available water in the reservoir was calculated as well.

Table 1: Potential water supply reservoir for several situations

	Water supply and period for a dry year	Water supply and period for a normal year	Water supply and period for a wet year
Reservoir spillway 0.73; including rainy season	1,984 m ³ 5.7 months	2,424 m ³ 7.0 months	3,039 m ³ 8.7 month
Reservoir spillway 0.73; after last overflow-event	1,865 m ³ 5.4 months	1,531 m ³ 4.4 months	2,192 m ³ 6.3 month
Reservoir spillway 1.00; including rainy season	2,401 m ³ 6.9 months	2,807 m ³ 8.1 month	3,178 m ³ 9.1 month
Reservoir spillway 1.00; after last overflow-event	2,285 m ³ 6 months	1,926 m ³ 5.5 month	2,320 m ³ 6.7 month

4.2 Alluvial aquifer

The MODFLOW model has been used to analyze the hydrological characteristics of the alluvial aquifer. An analysis was made for the natural losses in the period after a single river flow event. The total amount of water that can be stored in the alluvial aquifer is 630 m^3 (over the section of 200 m, which is used as the design criterion of the sand storage dam). The calculated total amount of evapotranspiration loss is 88 m^3 (14%) and the seepage loss to the underlying granite layer is 529 m^3 (86%). The in- and outflow through the alluvial aquifer is 13 m^3 (2%), which is small compared to the other flows. An overview of the water balance is shown in figure 7. The same analysis was done for the situation with a sand storage dam constructed in the alluvial aquifer. Due to the heavy weathering conditions of the underlying granite the seepage loss is very large in the natural situation. A note has to be made that the model simulated an impermeable layer (clay, dolomite, fresh granite) on the bottom of the sand storage dam, because sand storage dams are always constructed above such layers (based on field observations in southern Zimbabwe). The total amount that can be stored in the sand storage dam is 980 m^3 . The maximum water abstraction from the sand storage dam equals 603 m^3 (62%) and the only natural loss is due to evapotranspiration (38%). The total evapotranspiration loss becomes constant, because the evaporation becomes negligible when the water table recedes 0.9 m below the surface of the alluvial aquifer (Wipplinger, 1958; Nord, 1985; Borst and DeHaas; 2006).

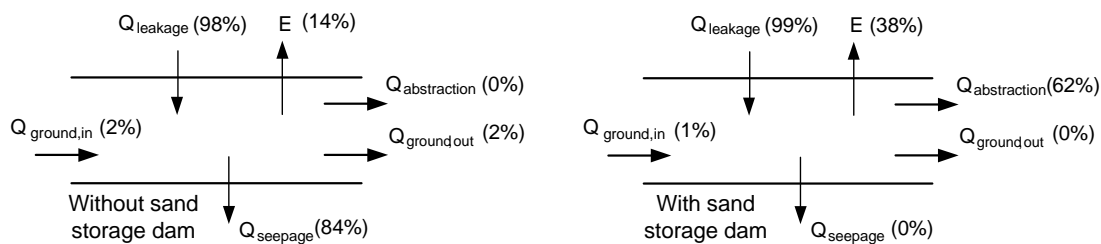


Figure 7: Water balance alluvial aquifer for situation without (left) and with sand storage dam (right).

For the calculation of the potential water supply the abstractions from the sand storage dam were held constant $7.0 \text{ m}^3 \text{ day}^{-1}$. This is approximately the amount of daily domestic water use plus the water needed to maintain the small gardens surrounding the reservoir. An advantage of a sand storage dam is that water does not have to be used immediately. However, the longer water is stored behind the dam, the larger the amount of natural losses becomes. Figure 8 provides insight into the relation between the potential water supply and the start of abstractions after the last river flow event for the sand storage dam in the alluvial aquifer of the Mnyabezi River

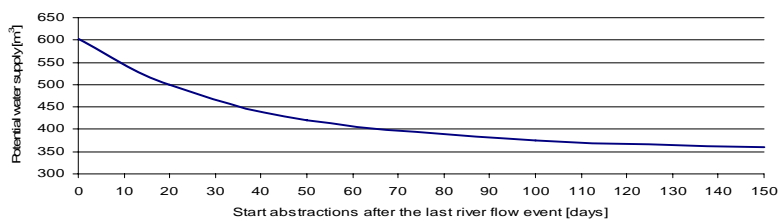


Figure 8: Amount of water storage in the sand storage dam over time without abstractions (only loss is evaporation)

The total water supply after the last dam overflow event from the alluvial aquifer of the Mnyabezi River in the current situation equals 123 m³. In that situation, the alluvial aquifer can provide water for only 14 days. In the situation of the sand storage dam, water is provided for a maximum of 70 days. The total potential water supply then becomes 603 m³. When the water is not used directly, but for example after 100 days, the total potential water supply is 375 m³ for a maximum period of 45 days. Table 2 provides an overview of the results of the alluvial aquifer in several situations.

Table 2: Potential water supply alluvial aquifer for several situations

	Water supply and period for a dry year	Water supply and period for a normal year	Water supply and period for a wet year
Alluvial aquifer; including rainy season	193 m ³ 0.8 month	235 m ³ 1.0 month	242 m ³ 1.1 month
Alluvial aquifer; 0 days after last overflow-event	123 m ³ 0.5 month	123 m ³ 0.5 month	123 m ³ 1.5 month
Sand storage dam; including rainy season	673 m ³ 2.6 month	715 m ³ 2.8 month	800 m ³ 3.1 month
Sand storage dam; 0 days after last overflow-event	603 m ³ 2.3 month	603 m ³ 2.3 month	681 m ³ 2.5 month
Sand storage dam; 100 days after last overflow- event	375 m ³ 1.5 month	375 m ³ 1.5 month	439 m ³ 1.7 month

5. Discussion

It is interesting to investigate the combined use of both water storage measures. The results show that the period of water supply extends for 1.5 to 1.7 months after the reservoir dried out. This makes the total period of water supply 7.2 months in a dry year and 10.4 months in a wet year. Heightening the spillway increases this period to respectively 8.4 (water supply = 2,776 m³) and 10.8 months (water supply = 3,617 m³). Thus, there is still to bridge a gap of maximum 3.6 months and minimum 1.2 months, depending on the rainfall that year.

The former section presents a lot of exact figures, while there is of course an uncertainty in outcomes. The rainfall-runoff model was calibrated on only one rainfall event, which causes a large uncertainty in the amount of inflow into the reservoir model. Nevertheless, the drying process of the reservoir was measured quite well. Since the main interest of the study is to calculate the potential water supply after the main rainy season, the water balance results of the reservoir still provide useable outcomes. Besides, rainfall events in the semi-arid region of southern Zimbabwe are usually very heavy, which cause dam

overflow in the reservoir and complete saturation of the alluvial aquifer anyway. Another large uncertainty occurs in the calculations of the water balance of the proposed sand storage dam, because the outcomes could not be verified with measured data. Nevertheless, the calculated drying time results (2 - 3 months) are comparable with the information obtained during field visits at similar sand storage dams in southern Zimbabwe.

6. Conclusions

In this study the potential water supply of the upper-Mnyabezi catchment was calculated for current conditions and after implementation of storage capacity interventions. These measures are heightening the spillway of the 'Mnyabezi 27' dam and constructing a sand storage dam in the alluvial aquifer of the Mnyabezi River. Three coupled models were used to simulate the hydrological processes in the Mnyabezi catchment: a rainfall-runoff, a reservoir and a groundwater model. The potential water supply in the Mnyabezi catchment under current conditions ranges from 2,107 m³ in a dry year to 3,162 m³ in a wet year and dries out after 5.7 to 8.7 months. After implementation of the two storage measures, there will still be a "drought gap" to bridge of maximum 3.6 months and minimum 1.2 months, depending on the rainfall that year.

For the Mnyabezi catchment the alluvial aquifer is too small to create a large storage capacity, and can only be used as an additional water recourse. However, when an ephemeral river is underlain by a larger alluvial aquifer, a sand storage dam is an efficient way of storing water in the semi-arid regions of southern Zimbabwe. An alluvial aquifer twice as large as the Mnyabezi catchment, could store between 1,000 m³ to 1,500 m³ water (depending on the seepage losses) for the whole year. Assuming the same domestic water use as in the Mnyabezi catchment, the sand storage dam could supply water for 4.5 to 7.0 months. In this study, the effects of a sand storage dam were analyzed for a small catchment. The modeling methods and obtained results are usable for a better understanding of the hydrological processes in larger alluvial aquifer systems in the Mzingwane catchment.

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