Surface/groundwater interaction: Using water balancing, hydraulic modeling and real-time monitoring to develop a truly Integrated Decision Support System (IDSS)

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Abstract

In drier parts of Southern Africa, water reservoir releases into riverbeds often lead to significant losses of flow volumes (*river losses*) and result in supply shortages for downstream water users. *River losses* occur as a result of a number of underlining variables and these variables need to be identified and quantified. The Blyde River and Olifants River Systems (BRORS), in northern South Africa show such *river losses.* In an effort to improve water release efficiency, the Department of Water Affairs and Forestry, South Africa (DWAF) initiated a study to develop integrated water resource operating rules. The BRORS is characterized by relative sandy river channels and leakage from river channels to the subsurface may contribute to substantial *river losses.* As part of the study an operating analysis will be carried out for the System using the water resource planning model. The river loss dependant variables for use with the water resources planning model will be determined using hydrodynamic modeling. This process involves three distinct steps, namely, water balancing, hydraulic modeling and monitoring. However, key to calibrating the model is real-time monitoring data to understand the dynamic flows between surface and groundwater. Real-time monitoring data were obtained by releasing water from the Blyderivierspoort Dam, and decreases in flow volumes were measured at a number of weirs. Results from real-time monitoring were used to calibrate the model and quantify surface/groundwater interaction. The model will be used to review different scenarios. Results from scenario testing will be used as input criteria for development of a truly Integrated Decision Support System (IDSS). Water resource managers will be able to use the IDSS and operate the System in a more efficient manner. Study results will guide future studies, having similar conditions, on the significance between surface / groundwater interaction and river losses. The conceptual model used to solve this problem as well as the constraints of the study are described in more detail.

Keywords: *Blyde River System, hydraulic modeling, real-time monitoring, surface/groundwater interaction.*

1 Introduction

The Blyde River catchment is situated in the Mpumalanga Province of South Africa. The catchment contains two reservoirs, namely Ohrigstad and Blyderivierspoort Dams. The dynamics of the Blyderivierspoort Dam catchment are unusual; as the natural mean annual runoff (MAR) is calculated as 362 million m^3/annum for the period 1920 to 1987 whereas the net capacity available in the dam is 48 million m^3. This provides a relationship of MAR to capacity of 7.5. This is clearly visible in the historical records of the Dam, which spills for most of the year. The 1 in 50 year long term stochastic firm yield of Blyderivierspoort Dam is 150 million m^3/annum. This is on a par with the 2005 demands on the Dam of 150.3 million m^3/annum. The dam is therefore currently in balance, and at present cannot satisfy any further demands.

The main land-uses in the Blyderivierspoort Dam catchment are commercial timber and irrigated agriculture. Some small towns such as Pilgrim's Rest and Hoedspruit are also situated in the catchment and use water from the catchment. Blyderivierspoort Dam has long been the centre of some controversy. The dam provides water to irrigators of the Blyderivierspoort Irrigation Board and Lepelle Northern Water who abstract from the Phalaborwa Barrage (a gated weir structure) and provides water to Phalaborwa town and surrounding mines as well as the Kruger National Park in the form of the Environmental Reserve releases. Lepelle Northern Water operates the Barrage and therefore controls water releases for downstream users – the most important being the Environmental Reserve requirement of the Kruger National Park. The Kruger National Park has often expressed its dissatisfaction with the amount of water that they receive and have therefore started to request more releases from Blyderivierspoort Dam. However, as already stated Blyderivierspoort Dam is currently in balance, and at present cannot satisfy any further demands.

A study was initiated in 2005 to compile operating rules for Blyderivierspoort Dam as a result of the sensitive issues described above. These rules were prepared in the form of a simple rule curve using existing information on the current demands and release patterns. However, certain assumptions especially regarding "river losses" were made which directly affected the outcome. The validity of these assumptions was uncertain and, as a result, a further study was initiated. The first of these assumptions involved the loss component of the Dam. The water released from Blyderivierspoort Dam travels for approximately 50kms in the Blyde River and a further 53kms in the Olifants River before it reaches the Phalaborwa Barrage. It was assumed that 30% of the allocation of Lepelle Northern Water (51 million m^3 / annum) did not reach the Barrage as a result of transmission losses along the way. In addition, Lepelle's full demand of 51 million m^3 / annum was placed on Blyderivierspoort Dam in order to produce the operating rule curve. This is, however, not the case in practice, as Lepelle also makes use of water from the Olifants river system which reaches the Barrage. As a result, Lepelle actually obtains part of its allocation from the Olifants River and only part from the Blyde River.

The follow-up study started in 2006 and the main objectives are to determine new operating rules for Blyderivierspoort Dam by:

- Using practical measurements and water balance calculations to gain a better understanding of the "river loss" component of the demand on Blyderivierspoort Dam; and
- To model the entire Olifants system in order to determine the actual portion of Lepelle's demand which is obtained from Blyderivierspoort Dam and the portion augmented by the Olifants.

The determination of loss dependant variables for use with the water resources planning model involves the determination of the relative magnitude of losses within the river system between Blyderivierspoort Dam and Mamba flow gauge downstream of the Phalaborwa Barrage through a combination of water balancing, hydrodynamic modeling and monitoring. Figure 1 provides a locality map of the study area.

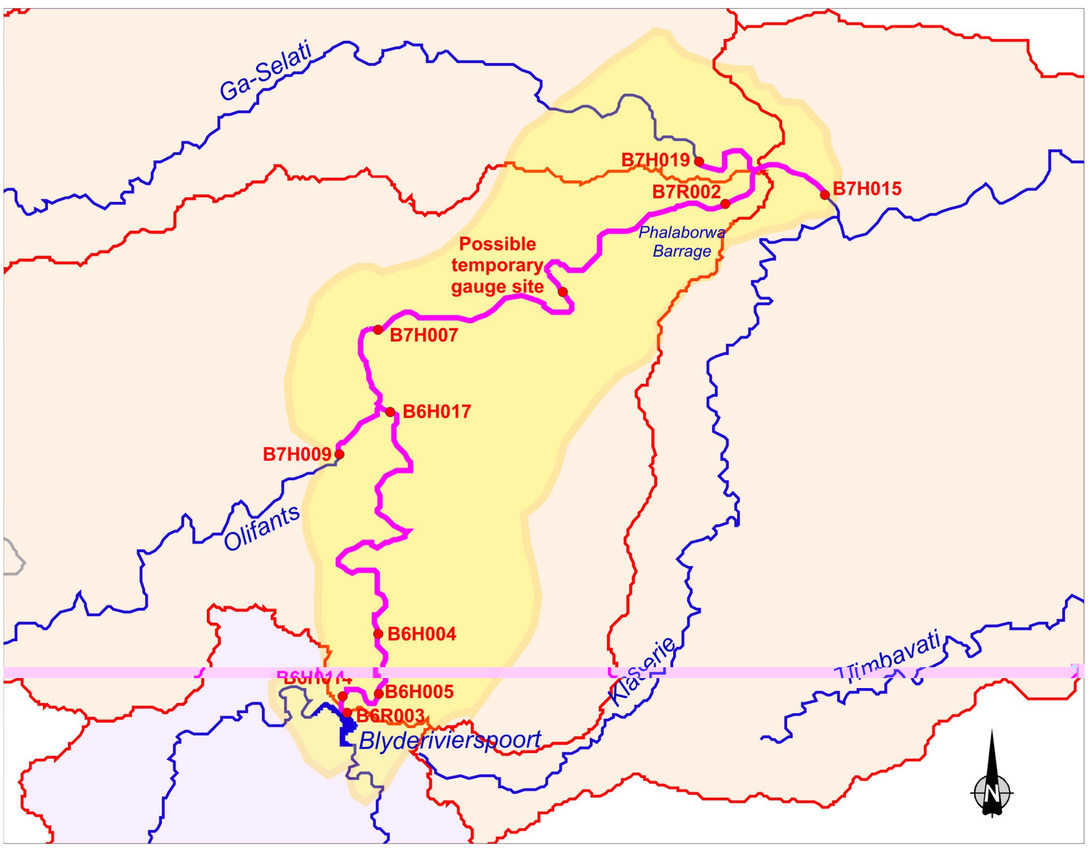

Figure 1. Location of study area

The Study is ongoing and will be completed in July 2008. This paper outlines the conceptual model proposed to determine the loss dependent variables and some preliminary findings, especially with regards to the monitoring of flows.

2 Conceptual model

The determination of loss dependant variables for use with the water resources planning model involves the determination of the relative magnitude of losses within the river system between Blyderivierspoort Dam and the IFR site downstream of the Phalaborwa barrage through a combination of water balancing, hydrodynamic modelling and monitoring.

To facilitate a structured approach, it is proposed to demarcate the river system into three distinct river sections (see Figure 2), each which is bordered on both upstream and downstream sides by reliable gauging stations. These sections, chosen on the basis of water use, river loss profiles and availability of gauging structures, are:

- The upper section including the Blyde river downstream of Blyderivierspoort Dam up to the confluence and the Olifants River from B7H009 (Liverpool) to B7H007 Oxford;
- The middle section stretching form B7H007 (Oxford) to the Phalaborwa barrage; and
- The lower section from the Phalaborwa barrage to B7H015 including the section of the Selati River from B7H019 to the confluence with the Olifants River.

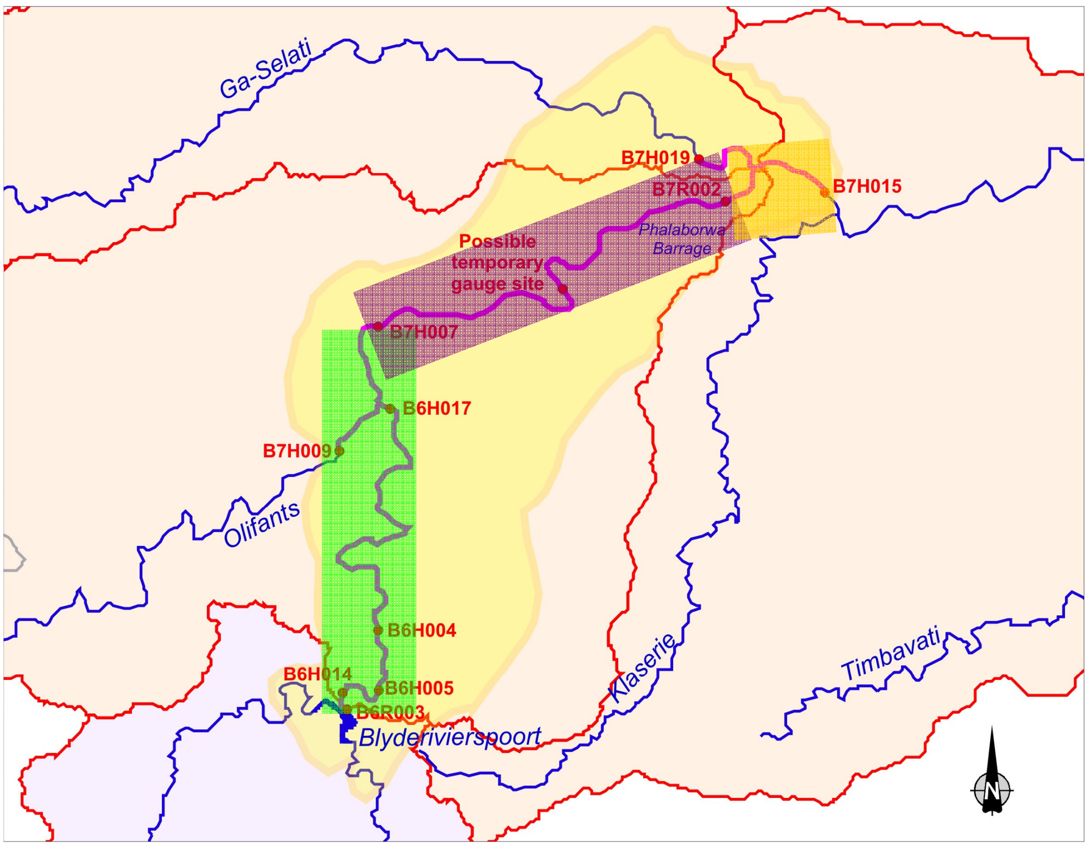

Figure 2. Distinct river sections

The first step in the process would be to perform a water balance for each of these river sections to determine the main variables for that particular section. This will involve an audit or water balance of processes contributing to river system inflows and outflows as well as the mechanism(s) controlling river losses and abstractions. Subsequent adjustment of variables controlling the water balance will be used in the hydrodynamic model to test strategies for water management downstream of Blyderivierpoort Dam.

The second step involves the use of a hydrodynamic model to quantify the magnitude of losses by a comparison of simulated and recorded outflows at the downstream boundary of each river section. Whilst observed flows include the effects of attenuation and river losses, it will be assumed that a simulation of flows by means of a hydrodynamic model will only include the effects of natural attenuation by floodplains and channel storage. A comparison of observed and simulated flows will therefore reveal the magnitude of river losses in excess of the attenuating effects of river channel and floodplain storage.

The third step involves actual monitoring of flows in the river at different spots. The river system has benefited from the installation of gauges at a number of locations throughout the system. Comparison of the incremental flows for river reaches between gauges can provide observed evidence of river losses. However, due to problems with siltation and flow bypassing the operation of some gauges has ceased and the availability of concurrent records is therefore limited. A request has been made to DWAF – Hydrology: Mpumalanga to re-instate one gauge and install two temporary gauges with a view to obtaining a full set of concurrent records of flow throughout 2007. This will be used in conjunction with the simulated results of the hydrodynamic model to confirm the magnitude and origin of river losses.

The following is a detail outline of the concepts, data requirements and procedures involved in each of the three aspects of the study.

2.1 Water balance

The main philosophy of the water balance evolves around the following two concepts (which are graphically represented in Figure 3):

- The first entails that the inflows into each system balances with the outflows of the system. Inflows comprise the upstream river inflow, rainfall on the water body itself, runoff, seepage from the surrounding area and return flows (in particular irrigation return flows). Outflows occur through the downstream river outflow, evaporation, evapo-transpiration, infiltration and abstraction. So called "river losses" are viewed as the imbalance between water entering the river system upstream and that which flows out of the system at the downstream side of the river section;
- The second entails the existence of a secondary sand aquifer which is primarily fed by the surface flows in the river channel. This secondary sand aquifer is in addition to the normal primary aquifer.

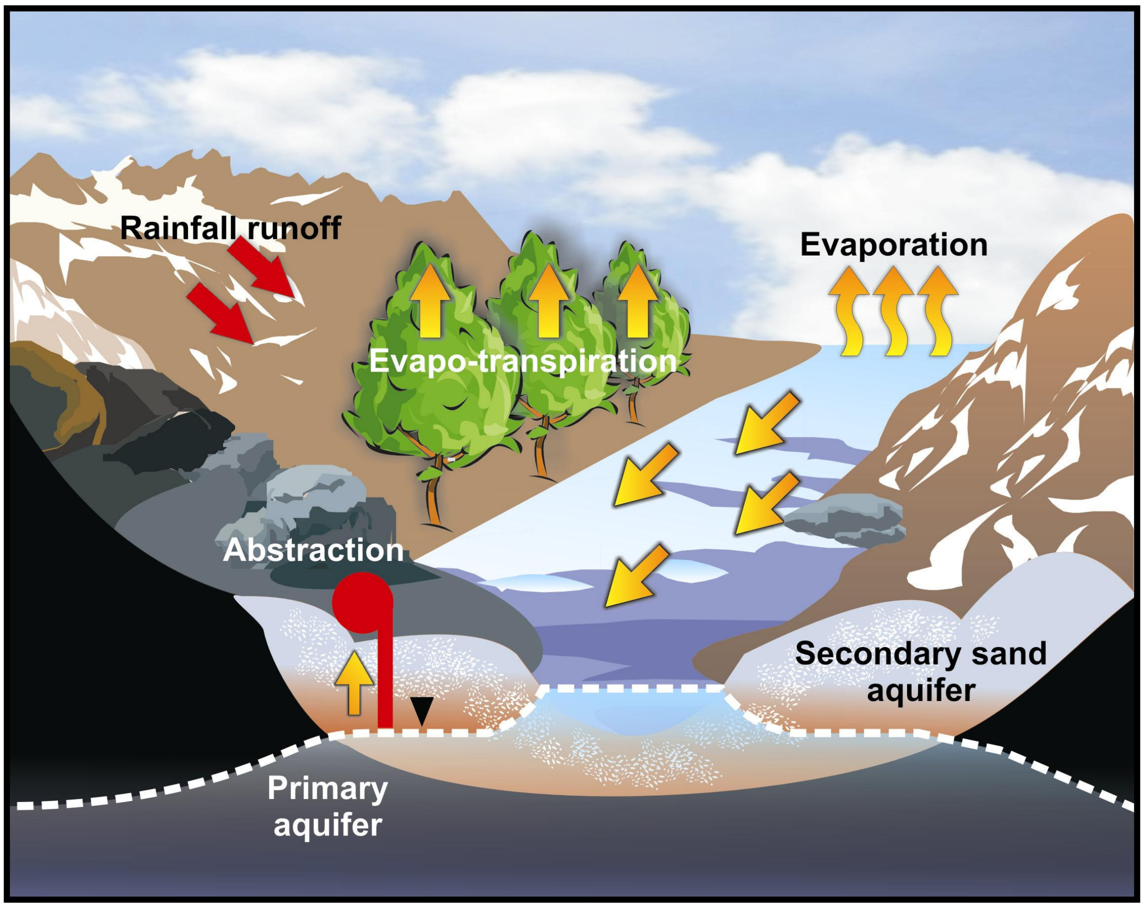

Figure 3. Conceptual water balance model

The determination of the absolute magnitude of river losses is not possible without an intensive and lengthy program of data collection. This is beyond the budget of this project and there is no guarantee that such a program would provide information that give reliable estimates of losses in all climatic and river flow conditions. Therefore, the aim is to identify the relative magnitude of components comprising inflows and outflows to the river channel. By so doing, a better understanding of the mechanisms involved in the creation of any losses will be gained. This will also enable the testing of water management scenarios through the adjustment of parameters controlling river losses to represent a range of possible river flow and climatic conditions.

Given the complexity of river processes and the difficulties in obtaining data it will be necessary to simplify some aspects of the water balance especially those relating to sub-surface flow related to the secondary sand aquifer. However, the intention is only to highlight gross disparities in the relative magnitude of components and this aim is not expected to be compromised by the assumptions being made. A daily water balance for the duration of typical travel times (+/- 3 days) will be carried out. It is envisaged that a number of water balances will be carried out to reflect the seasonal variation in river conditions.

The water balance will use recorded data wherever possible. Unfortunately, only climate, river flow and abstractions are monitored on a regular basis. Estimates of other components will rely on indirect means using generic data sets and some simplifying assumptions. In this regard it is proposed that the methodology developed by McKenzie and Craig (1999) be used to determine the evaporation and evapo-transpiration losses from the system.

To obtain compatibility in units it will be necessary to convert some measurements into volumes, such as rainfall, evaporation, evapo-transpiration, seepage and infiltration. Conversion will involve estimates of the surface area and wetted area of the riverbed. To this end, indicative values will be obtained from a combination of aerial photographs, satellite images and surveyed cross sections and will be ultimately checked during the hydrodynamic modelling stage. Adjustments will need to be made to account for seasonal variations.

2.2 Hydrodynamic model

A hydrodynamic model will be used to simulate the attenuating effects of channel and floodplain storage as well as evaluate the river losses (due to other river processes such as abstractions, evapo-transpiration and infiltration) determined during the water balance by comparing simulated flows and observed flows at the outlet of the relevant river section system and using the results of the evaluation to determine the dominant mechanisms controlling river losses. The results of the hydrodynamic model will also be used to fine-tune the river losses in the water balance.

The following concepts are of importance:

- Basic concept: Hydrodynamic models calculate water levels at discrete locations along a river reach;
- Model to be used: The client has requested that Mike11 is applied to the river system. This is a one-dimensional model where water levels at each location are assumed to be constant across the river valley. Mike11 requires inputs of flow hydrographs and downstream boundary conditions, together with elevations describing the geometry of the river valley and roughness factors representing the hydraulic properties of the riverbed.
- Calibration: It is normal practice for hydrodynamic model parameters to be calibrated. This would use a comparison of simulated and observed water levels and/or flows at significant locations within the river system. This ensures that model parameters represent the physical properties of the river system and the model is able to reproduce their combined influence on river flow and water level. To overcome the effects of river losses, it is proposed to calibrate the model during higher flood conditions and not during low flow conditions where the river losses will play a significant influence. (It will be assumed the difference between simulated and observed data reflects the processes of channel storage and river losses rather than model inaccuracy).

2.3 Monitoring

Key to performing the water balance is real-time monitoring data (both river flow as well as groundwater) to understand the dynamic flows between surface and groundwater. Initially at the start of the study it was assumed that it would be possible to monitor the water levels at a number of boreholes along the river channel. Subsequently it, however, became evident that no information or a relevant groundwater monitoring system exists. Theoretically the location of surface flow gauging stations at the upstream and downstream locations of the Blyde and Olifants rivers provides an opportunity to compartmentalize the behaviour of rivers within the system into suitable rivers sections that are particularly susceptible to losses. It should also provide the necessary data for comparison with the simulated output from the hydrodynamic model that will be used to determine the magnitude of losses.

With the exception of gauges at Essex (B6H017), Liverpool (B7H009) and Phalaborwa barrage (B7R002) all gauging stations have automatic recorders which are functioning. The upper river section comprising the Blyde River between the dam and the confluence is fairly well gauged, with a gauge just downstream of the dam (B6H005: Driehoek), one a quarter of the way down the river (B6H004: Chester) and one near the confluence (B6H017: Essex). The Essex gauge, however, is only suitable for low flow measurements of less than 1 m^3/sec.

To enable proper water balancing it has been requested to DWAF that the gauge at Liverpool gauging station be fitted with a temporary logger to determine the inflows from the Olifants main stem (without which water balancing of the upper and middle river sections would not be possible).

Outflows and abstractions from Phalaborwa barrage are also not known to be accurately monitored and the means of obtaining improved measurements for the middle river section are outlined below. Two new monitoring sites have been selected at locations between Oxford gauging station and the Phalaborwa barrage. These sites were equipped with loggers which records water levels every 12 minutes. This data are downloaded once a day and sent back to DWAF's real time system. As a result, the data can be viewed over the internet on an almost real time basis.

The last relevant flow gauge on the Olifants for the purposes of this study, is the gauge at Mamba (B7H015), which is located on the inside of the Kruger National Park boundary. Downstream of the Phalaborwa Barrage and upstream of Mamba gauge a significant tributary, the Ga-Selati, flows into the Olifants River, and the flow gauge B7H019 was used to determine the contributions.

Real-time surface monitoring data were obtained by releasing constant flows from the Blyderivierspoort Dam, and measuring the decreases in flow volumes at a number of weirs. Results from real-time monitoring were used to calibrate the model and quantify surface/groundwater interaction. The dry season of May to August 2007 was selected for the temporary flow monitoring exercise. Extra effort was also made to convince Lepelle Northern Water to keep accurate records of the operation of and abstractions from the Phalaborwa Barrage.

3 Conclusions

From the results of the study so far, the following important conclusions are drawn:

- The lack of available groundwater monitoring data will negatively influence the accuracy of the surface/groundwater interface results in the water balance. This, together with the shortcomings in the surface water monitoring system (especially Phalaborwa Barrage), will hopefully be negated to a certain degree by the temporary gauging in the middle river section as well as the simplification of certain aspects of the water balance; and
- At this stage the proposed conceptual model to determine the river loss dependant variables through a combination of water balancing, hydrodynamic modelling and monitoring still appear to be relevant.

References

McKenzie, RS, Craig, AR 1999. Evaporation Losses from South African Rivers. WRC Report No. 638/1/99. WRC, Pretoria, South Africa.