APPLICATION OF A WATER BALANCE MODEL TO INVESTIGATE GROUNDWATER-SURFACE INTERACTIONS FOR THE 13TH BIENNIAL GROUNDWATER DIVISION CONFERENCE AND EXHIBITION: GROUNDWATER: A NEW PARADIGM

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Abstract

The article presents the application of a water balance model as a preliminary tool for investigating groundwater-surface water (GW-SW) interactions along an alluvial channel aquifer located in a semi-arid climate in the central province of South Africa. The model is developed based on the conservation of mass; solute and stable isotopic mixing of the model components. Discharge measurements were made for the river segment inflow and outflow components using stream velocity-area technique. The Darcy equation was used to calculate the groundwater discharge from the alluvial channel aquifer into the river segment. Electrical conductivity (EC) and δ²H isotope were measured for the inflow and outflow components of the model as indicators of solute and stable isotopic ratios. Measurements were conducted during a low river flow once off period of October 2011 thus offering a great opportunity to assess GW-SW exchanges when other potential contributors can be regarded as negligible. The model net balance shows that the river interval is effectively losing water. The mass and solute balance approach provided close to a unique solution of the rate of water loss from the model. The model outcome provides a platform from which to develop appropriate plans for detailed field GW-SW interaction investigations to identify the mechanism through which the river is losing water.

Keywords

Water balance model; Groundwater-surface water; Groundwater discharge; Isotope; Alluvial channel aquifer

1 INTRODUCTION

A water balance model is based on the conservation of mass in a system that can be described by equations to represent some aspects of the physical system. The mass properties of the model can be combined with solute and isotopic mixing to describe both the physical, chemical and isotopic processes affecting water components of the system. When groundwater and surface water resources are treated as interlinked systems, then a water balance model can be used to improve the understanding of the GW-SW interactions.

A number of studies have demonstrated the use of water balance models to estimate groundwater contributions into the surface water. Measurements of discharge at the upstream and downstream of a river segment have been used in Devito et al (1996) and Cey et al (1998) to estimate groundwater contributions into surface water resources. Although the studies have been very useful, some of them lack clearly defined objective and approaches that can potentially save time and reduce expenses on field work. Without clearly defined objectives detailed field measurements of seepage flow, isotopic compositions, aquifer parameters does not always provide answers about the nature of GW-SW
It is also important to mention that the mere existence of alluvial channel aquifers in the vicinity of river systems does always signify connectivity and interactions between the resources.

Conceptual discussion and descriptions the with regard to the nature and modes of interactions that can occur between groundwater and surface water systems have been extensively covered in Tóth (1970), Sophocleous (2002) and Ivkovic (2009). In literature three major review papers by winter (1999), Sophocleous (2002), Woessner (2000) have addressed GW-SW interactions as a multidisciplinary field and outlined the state of the science as guidelines for field investigations. While the studies have made significant contributions in offering research methodology options, they have failed to give a basic approach to determine if detailed GW-SW field investigations are really necessary.

In this paper a water balance based approach that utilises once off measurements of river flow and groundwater discharge, solute concentration and $\delta^2$H isotopic ratio is used to investigate GW-SW interactions at a local scale. The main objective of the study is to demonstrate how a basic water balance model can be used as a preliminary tool in GW-SW interactions studies. Information gathered from the water balance is essential for planning purposes prior to detailed field investigations. Preliminary information gathered from a simple GW-SW water balance model can aid in prioritizing specific objectives of detailed field studies and thus resources can then be channeled on highly regarded aspects.

2 FIELD SETTING AND HYDROGEOLOGY
The case study area is located in Bloemfontein in the Free State Province of South Africa (Figure 1). The study area consists of both surface and groundwater resources. Groundwater resources in the study area include the alluvial channel aquifer and background terrestrial aquifer. Besides farm house boreholes, no significant groundwater development and utilization was identified in the vicinity of the site. The Modder River and the Krugersdrift dam are the two main surface water resources in the study area. Farmers around the site mainly use river water to meet their irrigation requirements. A weir (Figure 1) was built downstream of the Krugersdrift dam for flow measurements but it is large enough to impound water for irrigation and nature conservations.
The study area is characterised by arid to semi-arid climate. The area is generally dry and on average receives about 600 mm of rainfall per annum. During the 2010/2011 rain season the study area received
about 680 mm of rainfall. The riparian vegetation alongside the Modder River banks comprises of tall thorn trees, small Bushveld shrubs and thick grasses.

The general geology of the study area is characterised by shale, sandstone and mudstone outcrops of the Beaufort Group located in the Main Karoo Basin. The Main Karoo Basin overlies the central and eastern parts of South Africa. The sediments of the lower part of Beaufort Group (Adelaide Sub-group) within the local area of alluvial channel aquifer study comprises of unconsolidated quaternary deposits of calcrete, silt-clay and gravel-sands that overlie the shale bedrock. Sand and gravel unconsolidated deposits forms the most yielding hydrogeological unit of the alluvial aquifer system because of their naturally high hydraulic conductivity.

Surface topography slopes towards the Modder River and natural groundwater flow should conceptually flow towards the river. A seepage face discharge zone has been created at the contact area of the unconsolidated sediments and the underlying impermeable bedrock (Figure 2). The impermeable underlying bedrock unit retards the vertical downward movement of groundwater from the unconsolidated sediments and as a result it preferentially moves in the horizontal direction discharging into the river at the contact plane. Groundwater continuously discharges into the river through the seepage face and according to the farmer who stays closer to the site this phenomenon has been occurring for the last 50 years.

![Figure 2](image.png)

**Figure 2** A schematic showing groundwater flow in the unconsolidated sediments of the alluvial cover channel aquifer underlying the shale impermeable bedrock where discharges groundwater into the river at the seepage face; \( \Delta h \) is the average hydraulic head differences between local aquifer and discharging zone; \( L \) and \( b \) are the length and thickness of the seepage face respectively [m].
3 THEORY

3.1 Water balance model
A water balance model is the most important primary tool for investigating GW-SW interactions before any detailed field such as drilling of boreholes can be conducted. A water balance model is fundamental for determining the gaining or losing status of the groundwater and surface water resources. In other words, the outcome of the water balance model should provide direction and guidelines for the upcoming detailed GW-SW investigations. Fig. 3 shows the components of the water balance model at the site. It is important to highlight that the visible groundwater discharge at the seepage face does not represent all the groundwater in interaction with the river system along the study segment. It is possible that the river could be gaining groundwater or losing into the aquifer at other sections of the study channel segment.

Figure 3 A schematic showing the components of the water balance model at the study site.

The water balance model was developed based on the conservation of mass (Equation 1); mixing of solute (Equation 2) and stable isotope (Equation 3). Based on the conservation of mass, the inflow rate into the system should be equal to the outflow rate if there is no storage, loss or additional water into the system.

\[ Q_{RI} + Q_{GI} + Q_G - Q_L - Q_E = Q_{RO} \]

Equation 1

Where: \( Q_{RI} \) – measured river segment inflow rate (l/s); \( Q_{GI} \) – calculated visible groundwater inflow rate into the system (l/s); \( Q_G \) – unknown systems gain rate (l/s); \( Q_L \) – unknown systems loss rate (l/s); \( Q_E \) – evaporation loss rate (l/s); \( Q_{RO} \) – measured river segment outflow rate (l/s).

Equation 1 defines whether the river segment is gaining or losing. Evaporation losses during the measurement period were assumed to be negligible. Equation 2 and Equation 3 are then used to confirm the findings of mass balance analysis (Equation 1). The solute concentration and isotopic ratio of the system loses are taken to be equal to that of the river outflow assuming that uniform mixing will have occurred prior to the loses.

\[ Q_{RI} C_{RI} + Q_{GI} C_{GI} + (Q_G C_G or - Q_L C_L) = Q_{RO} C_{RO} \]

Equation 2
Where: \( C_{RI} \) – measured solute concentration of the river segment inflow; \( C_{GI} \) – measured solute concentration of visible groundwater inflow; \( C_{G} \) – solute concentration of system gains; \( C_{L} \) – solute concentrations of system losses; \( C_{RO} \) – measured solute concentration of the river segment outflow; Electrical conductivity \([\text{mS/m}]\) was used as a surrogate for concentration.

\[
Q_{RI}\delta_{RI} + Q_{GI}\delta_{GI} + (+Q_{G}\delta_{G} \text{ or } -Q_{L}\delta_{L}) = Q_{RO}\delta_{RO}
\]

Equation 3

Where: \( \delta_{RI} \) – measured isotopic ratio of the river segment inflow; \( \delta_{GI} \) – measured isotopic ratio of the groundwater inflow; \( \delta_{G} \) – isotopic ratio of system gains; \( \delta_{L} \) – isotopic ratio of system loses; \( \delta_{RO} \) – measured isotopic ratio of the river segment outflow; The isotopic ratio were measured in \([\%o]\).

4 METHODS AND MATERIALS

4.1 Discharge measurements

The discharge measurements were conducted during the low river flow period in October 2011. In general, low river flow volumes are easier to measure and handle. At the same time, low river flow periods also offers great opportunity to assess GW-SW exchanges when other potential external sources and sinks can be regarded to be negligible.

The inflow and outflow discharge is calculated as the product of mean velocity and cross-sectional area. Measurements were therefore made to determine the mean cross section area and mean stream velocity at the inflow and outflow positions of the model. In the absence of in built weirs, selection of the appropriate positions for measuring water outflow and inflow into the river segment was essential and the following were the key factors during considerations:

- A small and shallow river channel cross-section is preferable to avoid drowning.
- A river segment that has a fairly constant channel width is desirable to reduce the effects of width heterogeneities on measurements.
- The river segment should be clear of trees and any possible obstructions on water flow.

A dumpy level and staff rod were used to measure the depth from the water surface to river bed. Measurements were made at a series of points across the stream inflow and outflow positions thus dividing the cross sectional into segments. The total cross sectional area of the channel was computed from the summation of segment cross sectional areas.

Two points were marked and distance between the two points was measured. An orange peal float was thrown upstream of the first point and the time to reach the downstream point along the river interval was recorded for 10 set of readings. The average surface velocity was obtained by diving the distance travelled by the time. The surface stream velocity was multiplied by a factor of 85 % to convert it to mean velocity across the entire cross section (Costa et al. 2004).

Groundwater discharge that was visible from alluvial channel aquifer along the seepage face was determined using Darcy’s flow equation. Hydraulic flow properties of the alluvial channel were determined by (Gomo, 2011). Visible groundwater discharge into the model is at the seepage was classified as a known component.

4.2 Isotopes and solute measurements

The solute and isotopic ratio mixing in the model is based on the premises that complete mixing of solutes between the surface and groundwater occurs within the river segment. The concentration and
isotopic composition of river outflow and loses should therefore reflect properties of a complete mixture. It is assumed that the river bank and bed sediments have a negligible influence on the solute and isotopic mixing processes.

Electrical conductivity and δ²H were measured as indicators of the solute concentration and isotopic ratios. The measurements of these parameters were made in the visible discharging groundwater, river inflow and outflow components of the model. Electrical conductivity was measured using a field hand meter. Water samples for δ²H isotope measurement and were analysed by iThemba Environmental Isotope Laboratory of South Africa. It was assumed that all the losses in the system would occur after completing mixing had occurred and it’s solute and isotopic properties would be reflected in the river segment outflow water.

5 RESULTS AND DISCUSSION

5.1 Model inflow

5.1.1 River inflow (Q_RI)
The river inflow into the system was measured at position A which is at about 50 m downstream of the dam wall (Figure 1). Apparently there are no flow gauges at the dam and physical measurement was the most viable technique to quantify the river outflow into the model. In general, two types of flow can be associated with dam outflow at the site. There is a continuously maintained low flow and high flows that occur during scheduled dam releases. Figure 4 shows the measured cross-sectional area of flow at the river inflow section of the model.

![Figure 4 River cross-sectional area of flow at the inflow position of the model; the numbers indicate trapezoidal segments that were used to calculate the flow cross-sectional area; a meters below water surface](image-url)
The cross-sectional area of flow was calculated manually by considering the area of each trapezium area separately and then combining them to get the total area. Table 1 shows the total cross-sectional area of flow, velocity, discharge, EC and δ²H measured at the inflow of the model. Only one cross-sectional area of flow was measured at the inflow section because the channel width and depth were considered to be fairly constant for at least 10 m downstream of the first measurement position. The possible influence of the cross-sectional area on the river flow rate along the inflow segment was assumed to be negligible.

Table 1 Measurements of the total cross-sectional area of flow, surface velocity, discharge, δ²H stable isotopic ratio and EC at the inflow section of the model.

<table>
<thead>
<tr>
<th>Flow cross-sectional area [m²]</th>
<th>Average surface velocity [m/s]</th>
<th>Mean cross-sectional velocity [m/s]</th>
<th>Q_{RI} [l/s]</th>
<th>Q_{RI} [m³/d]</th>
<th>EC [mS/m]</th>
<th>δ²H [%o]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.96</td>
<td>0.36</td>
<td>0.31</td>
<td>295.88</td>
<td>25564.30</td>
<td>33.40</td>
<td>-3.92</td>
</tr>
</tbody>
</table>

5.1.2 Groundwater inflow (Q_{GI})

The visible groundwater inflow component was quantified by determining the alluvial channel aquifer’s natural discharge at the seepage face. Figure 2 shows the idealised schematic of the aquifer discharge zone at the seepage face. The seepage face length (L) is approximately 100 m. Based on the field observations at the seepage face, groundwater was considered to be discharging into the river through a thickness (b) of about 2 m above the shale impermeable bedrock. Horizontal hydraulic conductivity of the discharging aquifer thickness was determined using harmonic mean transmissivity derived from aquifer tests (Gomo 2011). The discharge rate was calculated using Darcy’s law (Equation 4).

\[ Q = K \cdot i \cdot A \]

Equation 4

Where: K – horizontal hydraulic conductivity in the discharging aquifer thickness (m/d), i – hydraulic gradient from the aquifer to the discharging face, A – cross sectional area of the discharging face perpendicular to the discharging flow (m²).

Table 2 shows the calculated groundwater discharge from the alluvial channel aquifer and the parameters that were used for the calculation. The EC and δ²H values in Table 2 were measured in the discharging groundwater at the seepage face.

Table 2 Calculated groundwater discharge from the alluvial channel aquifer into the river and parameters used for calculations; EC and δ²H of the discharging waters.

<table>
<thead>
<tr>
<th>L [m]</th>
<th>b [m]</th>
<th>i</th>
<th>T [m³/d]</th>
<th>K [m/d]</th>
<th>Q_{GI} [l/s]</th>
<th>Q_{GI} [m³/d]</th>
<th>EC [mS/m]</th>
<th>δ²H [%o]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>2.00</td>
<td>0.32</td>
<td>36.87</td>
<td>18.44</td>
<td>13.60</td>
<td>1174.98</td>
<td>126.02</td>
<td>-31.97</td>
</tr>
</tbody>
</table>
5.2 Model outflow

5.2.1 River outflow ($Q_{RO}$)
The river outflow component of the model was measured at position B (Figure 1). A shallow nick point characterises the segment of the river channel where the river outflow measurements were made. The segment of the channel is generally characterised by a compacted clay river bed of generally low permeability. Water losses along the bed that river segment were therefore assumed to be negligible in comparison to river flow. For river outflow segment, two cross-section areas of flow were measured because there was a significant variation in the channel width within 5 m from the first measurement position. Figure 5 and Figure 6 show the two flow cross-section areas that were measured along the outflow segment. Cross-section area 1 is located 5 m downstream of cross-sectional area 2.

![Figure 5 Measured cross-sectional area of flow (A) at the outflow segment of the model; the numbers indicate trapezoidal segments that were used to calculate the flow cross-sectional area.](image-url)
Figure 6 Measured cross-sectional area of flow (B) at the outflow segment of the model; the numbers indicate the trapezoidal segments that were used to calculate the flow cross-sectional

Table 3 shows measurements for the cross-sectional area of flow, velocity and flow rate at positions A and B along the outflow segment of the GW-SW system. Similar flow rates were calculated from the flow cross-section area and velocity measurements made at positions A and B which are just 2 m apart. The ability of the measurement method to produce closely comparable results is a reflection of its precision and therefore reliability. An arithmetic average of the outflow discharge measured at point A and B was used in the model.

Table 3 Measurements of the total cross-sectional area of flow, surface velocity, discharge, \( \delta ^{2}H \) stable isotopic ratio and EC at the outflow segment of the model.

<table>
<thead>
<tr>
<th>Position</th>
<th>Flow cross-sectional area ([\text{m}^2])</th>
<th>Average surface velocity ([\text{m/s}])</th>
<th>Mean cross-sectional area velocity ([\text{m/s}])</th>
<th>(Q_{0}) ([\text{l/s}])</th>
<th>(Q_{0}) ([\text{m}^3/\text{d}])</th>
<th>EC ([\text{mS/m}])</th>
<th>(\delta ^{2}H) ([/_{OO}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.39</td>
<td>0.56</td>
<td>0.48</td>
<td>186.00</td>
<td>16070.69</td>
<td>37.6</td>
<td>-6.17</td>
</tr>
<tr>
<td>B</td>
<td>0.35</td>
<td>0.62</td>
<td>0.53</td>
<td>186.11</td>
<td>16079.52</td>
<td>37.6</td>
<td>-6.18</td>
</tr>
</tbody>
</table>

5.3 Model net balance
The model net balance gives an indication of whether the river channel is effectively gaining or losing water. It is however possible for the river to be gaining while at the same time losing but the net effect is important for giving an overall understanding of the GW-SW exchanges. The model net balance should quantify the unknown losses or gain thereby giving a platform for detailed field investigations to identify
the nature of the exchanges. A combination of mass, solute and isotopic mixing balances was used to determine the net balance of the model.

Based on mass balance (Equation 1), a comparison of the total inflow and outflow shows that the river interval is effectively losing water (Table 4). Assuming that there is conservation of mass, solute concentration (Equation 2) and δ²H isotopic ratio (Equation 3) in the system the three approaches should give a unique solution for the net balance. In this instance, a unique solution implies that the rate of water loss determined from the mass balance should be equal to the one determined using solute concentration and δ²H isotopic ratio. It was assumed that that loses would occur after complete mixing of different waters in the system such that the solute concentration of the lost water will be equal to the concentration of the river outflow.

Shown in Table 4 are the measured and calculated components of the water balance model based on the mass, solute concentration and δ²H isotopic ratio. The rate of water loss from the model determined using the mass and solute mixing balance only differs by 1.07 l/s thus providing close to a unique solution. However on the other hand, the rate of water loss from the model determined using the mass and isotopic ratio mixing balance differs by 9.48 l/s. The big differences between the losses determined by mass and isotopic ratio mixing balance approaches is most likely because isotopic ratio of the water is more sensitive to evaporation than the EC. The overall effect is that the isotopic ratio balance approach would then indicate as if more losses occur due to evaporation than when the solute balance approach.

Table 4 Measured and calculated components of the water balance model based on the mass, solute concentration and δ²H isotopic ratio.

<table>
<thead>
<tr>
<th>Mass balance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{RI}$[l/s]</td>
<td>$Q_{GI}$[l/s]</td>
</tr>
<tr>
<td>295.88</td>
<td>13.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solute mixing balance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{RI}C_{RI}$[l/s mS/m]</td>
<td>$Q_{GW}C_{GI}$[l/s mS/m]</td>
</tr>
<tr>
<td>9882.48</td>
<td>1713.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotopic ratio balance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{RI}\delta^{2}$H$_{RI}$[l/s %/oo]</td>
<td>$Q_{GI}\delta^{2}$H$_{GW}$[l/s %/oo]</td>
</tr>
<tr>
<td>-1159.86</td>
<td>-434.77</td>
</tr>
</tbody>
</table>

In general, the visible groundwater discharging at the seepage contributes 3% of the total inflow into the system while about 32% of the total inflow is lost from the river segment. Potential sinks of water lost from the river could be other adjacent aquifers, bank storage, and river bed storage loss. The next stage of the GW-SW investigations would then be focused on identifying where and how the channel is losing water. It will also be important to identify the mechanisms of the of GW-SW exchanges along the channel.
interval which can be followed quantification. Although it is visible in this current study that groundwater is discharging into the river at the seepage face, it does not imply that river is gaining from all adjacent aquifers. It is possible for a river to be gaining water at certain sections while possibly losing on other sections.

5.4 Model uncertainty
Unlike the other measured model parameters; the thickness of the aquifer at the discharging seepage face was rather assigned based on geological understanding and visual observations made on the site. In other words, this parameter does not have an absolute measured value; it can vary depending on the observer and understanding of the site. A question can therefore be raised as to what will be the effect of changing the discharging aquifer thickness on the net balance of the model. If the aquifer thickness is assumed to vary between 0.1-2.0 m, this would decrease the groundwater discharge into the model thus effectively increasing the difference between $Q_L$ estimated from the 3 approaches (Table 5). It is important to mention that the difference of $Q_b$ between mass and solute mixing approaches that result from varying the aquifer discharge thickness from 0.1-2.0 m is still within the same order (0-10 l/s) the thereby justifying the use of a 2 m aquifer thickness. In general, the mass balance approach is least sensitive to changes in aquifer discharge thickness because the calculations are based on physical measurements. The isotopic approach is more sensitive to the changes in aquifer thickness.

Table 5 Water balance model loss rates ($Q_L$) calculated when aquifer thickness is varied from 0.1-2.0 m.

<table>
<thead>
<tr>
<th>$b$ [m]</th>
<th>$Q_{GW}$ [l/s]</th>
<th>$Q_L$ [l/s] (Mass)</th>
<th>$Q_L$ [l/s] (Solute)</th>
<th>Absolute difference of mass $Q_L$ and solute $Q_L$ (Isotopic)</th>
<th>$Q_L$ [l/s] (Isotopic)</th>
<th>Absolute Difference of mass $Q_L$ and Isotopic $Q_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>17.65</td>
<td>127.48</td>
<td>135.93</td>
<td>8.45</td>
<td>146.98</td>
<td>19.51</td>
</tr>
<tr>
<td>0.50</td>
<td>16.80</td>
<td>126.63</td>
<td>133.08</td>
<td>6.46</td>
<td>140.05</td>
<td>13.42</td>
</tr>
<tr>
<td>1.00</td>
<td>15.73</td>
<td>125.56</td>
<td>129.50</td>
<td>3.94</td>
<td>131.32</td>
<td>5.77</td>
</tr>
<tr>
<td>2.00</td>
<td>13.60</td>
<td>123.43</td>
<td>122.36</td>
<td>1.07</td>
<td>113.95</td>
<td>9.48</td>
</tr>
<tr>
<td>3.00</td>
<td>12.29</td>
<td>122.12</td>
<td>117.97</td>
<td>4.15</td>
<td>103.28</td>
<td>18.84</td>
</tr>
<tr>
<td>4.00</td>
<td>9.33</td>
<td>119.16</td>
<td>108.05</td>
<td>11.11</td>
<td>79.14</td>
<td>40.02</td>
</tr>
<tr>
<td>5.00</td>
<td>7.20</td>
<td>117.03</td>
<td>100.90</td>
<td>16.12</td>
<td>61.74</td>
<td>55.29</td>
</tr>
</tbody>
</table>

5.5 Planning for detailed investigations
The outcome of such a simple water balance model can assist in developing specific objectives for detailed GW-SW interaction investigations. In this case study, the model shows that the river segment under investigation is effectively losing water and thus detailed field investigations might focus on:

- Identification of positions along the river channel where the loss is occurring.
- Determination and description of the mechanism through which the water is lost from the river segment.
• Quantification of the loss at identified positions along the river segments. Seepage meters can also be installed to help in quantifying the exchanges.

In general, if for instance the river model is gaining, then one will have to consider the possible contribution of groundwater and interflow. When the river segment is losing, then the potential effects of evapotranspiration, aquifer gain, and bank loses can be evaluated during detailed investigations.

Although the proposed application of the water balance model to investigate GW-SW interactions does not consider changes that may occur in time and space it never the less provides a good platform for planning purposes. It is also important to mention that the effectiveness of the water balance model as a preliminary tool to investigate GW-SW interactions rely on the precise measurement of the known model component. It is important to make all the measurements in the shortest possible time to reduce the influence of external factors such evaporation on solute and isotopic compositions.

The thesis behind the application of a water balance preliminary tool for GW-SW interaction is based on the premise that “If you do not know what to investigate then you cannot know where and how to measure it and ultimately you will not understand it”.

6 CONCLUSIONS
Clearly, a good understanding of the application of water balance models as a preliminary tool to study GW-SW interactions can assist groundwater and surface water scientists prior to detailed field investigations. The model net balance shows that the river interval is effectively losing water. The water balance model proved essential for establishing the gaining or losing “status” of the river system. Once the “status” has been established efforts can then be directed at identifying the positions and mechanisms of interaction and quantifications of the exchanges which will be followed by the measurement of specific exchanges. The water balance model can therefore be used as a preliminary tool for providing insights on what to measure during detailed field investigations of GW-SW interactions.

7 ACKNOWLEDGMENTS
We wish to acknowledge the support and funding from the Water Research Commission of South Africa (K5/1760 Bulk Flow and K5/1766 Light Non Aqueous Phase Liquid projects), without them this research would not have been possible. The assistance from the Department of Water Affairs in drilling the boreholes at the test site is also greatly appreciated. Technical field assistance that was offered by Pacôme D. Ahokpossi (Ph.D student, University of the Free State) during river flow measurements is greatly appreciated. Furthermore, we wish to acknowledge the University of the Free State for secondary funding for the analysis of samples and other technical work.

8 REFERENCES


