Monitoring the bank storage dynamics component of the riparian water balance in the Sabie River, Kruger National Park

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Abstract

Transpiration by riparian vegetation is a major consumptive water use in natural river systems, and must be considered when making water allocations for environmental conservation. Transpiration needs can be estimated by integrated modelling of bank storage dynamics, transpiration processes, and river hydraulics. Development and application of the bank storage model require field data describing the response of the phreatic surface to river stage fluctuations, the spatial and temporal distributions of water content in the unsaturated zone, and the geometry of the bedrock boundaries. A site on the Sabie River in the Kruger National Park, South Africa, is currently being monitored to collect such data. The phreatic surface response is interpreted to improve understanding of the nature of the subsurface flow, and its response to transpiration. Measurement of soil moisture by neutron probe and laboratory analysis has confirmed the effectiveness and reliability of the neutron probe method, and provided the necessary calibration data. Delineation of bedrock boundaries by physical probing and the use of ground-penetrating radar has demonstrated the effectiveness of the radar technique.

Introduction

Bank storage dynamics in the riparian zone adjacent to a river channel determines water availability to riparian vegetation, and is an essential component of the riparian water balance. Although few studies have dealt directly with bank storage as a source of soil moisture in the riparian zone, considerable attention has been focused on the seepage from unlined canals due to its importance for the management of water resources (e.g. Todd and Bear, 1961; Bouwer, 1969; Worstell, 1976; and Wachyan and Rushton, 1987). These seepage studies generally involve the development of seepage rate formulae using theoretical analyses, laboratory studies, and limited field data. Wachyan and Rushton (1987) suggest that further detailed modelling and field studies be undertaken on the conditions within the soil zone adjacent to the channel.

A hydrological study involving monitoring groundwater response to river stage fluctuations at a site on the Skeena River floodplains in British Colombia, Canada, is described by Beaudry (1989). Specific high quality data were collected over the period 1986 to 1988, using intensive and extensive networks of piezometers located adjacent to backchannels. The data were collected to provide an understanding of the hydrology and environmental characteristics of the floodplains. Inadequate data on the physical characteristics of the site unfortunately preclude its use for verification of the numerical bank storage dynamics model described by Birkhead and James (1993).

The design and installation of monitoring systems for river stage and bank storage at a study site on the Sabie River, Kruger National Park (KNP) are presented here, and preliminary results are discussed. These data are necessary to verify a computational bank storage dynamics model.

The seven major rivers flowing through the KNP (Crocodile, Sabie, Olifants, Letaba, Shingwedzi, Levuvhu and Limpopo Rivers) all rise beyond its western border and drain catchments that are being subjected to increasing pressure for their available land and water resources (Fig. 1). This pressure results from the escalating

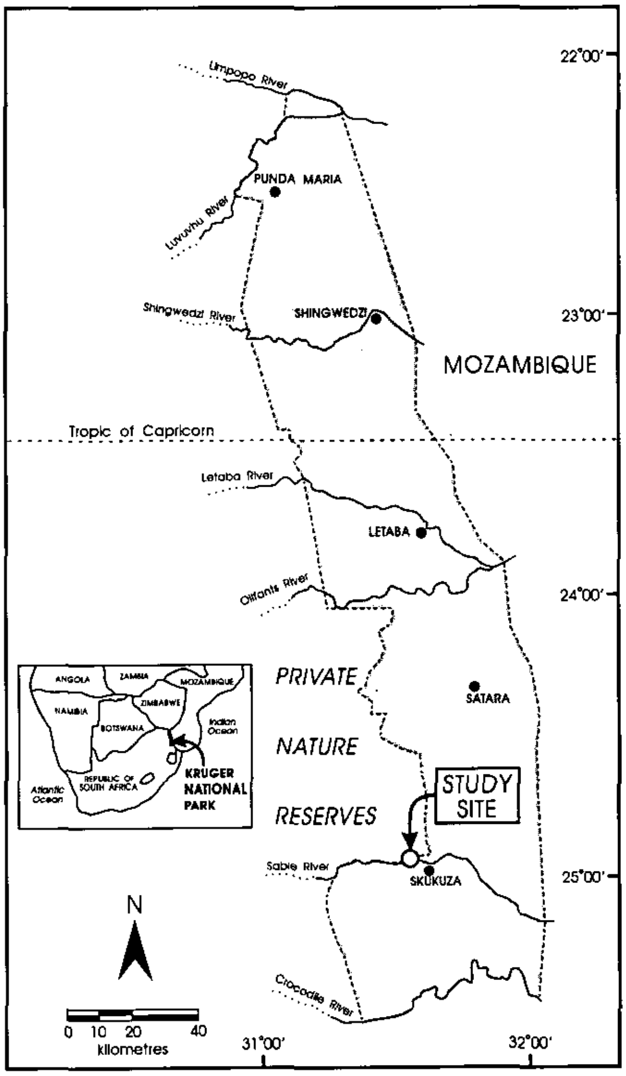

Figure 1
Location of the study site along the Sabie River in the Kruger National Park

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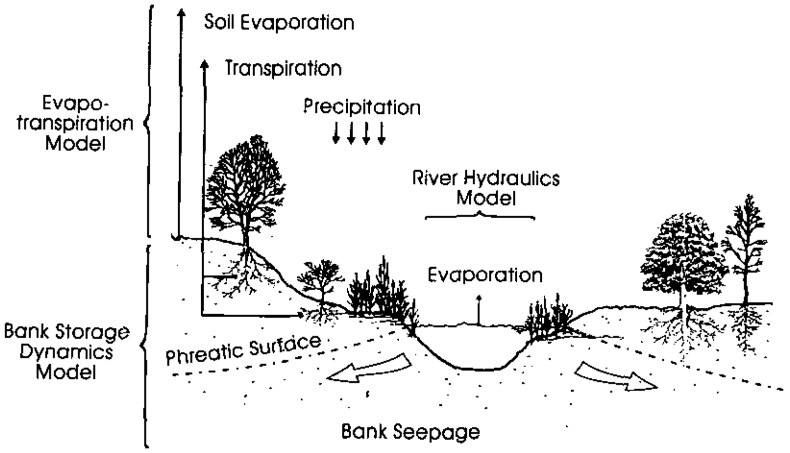


Figure 2
Two-dimensional riparian water balance showing component models

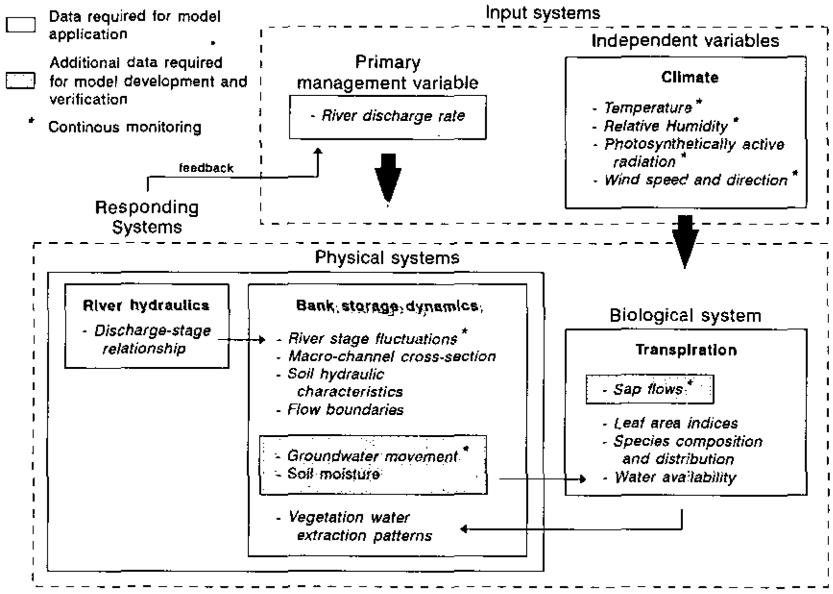


Figure 3
Data required for development and application of the riparian water balance model, with the fundamental interactions between the components of the system

human population growth in the rural areas immediately west of the KNP, coupled with increasing afforestation in the upper catchments and agricultural development. The projected increase in the human population in these rural areas is from 2.7 m. in 1985 to 4.7 m. by the year 2000 (Urban Foundation, 1990). The associated increase in the domestic, mining, municipal and industrial water consumption within the Sabie River catchment is estimated at 363%, from 7.4 x 10^6 m^3/a in 1985 to 34.7 x 10^6 m^3/a by the year 2000 (Chunnet, Fourie and Partners, 1990a). Afforestation in the Sabie River catchment has resulted in an estimated 17% reduction in the mean annual runoff, with no further significant reduction expected under current permit restrictions. The estimated increase in water consumption by irrigation is 130%, from 99.3 x 10^6 m^3/a in 1985 to 228.1 x 10^6 m^3/a by the year 2010 (Chunnet, Fourie and Partners, 1990a; b).

This increasing development has resulted in the rivers that flow through the KNP in the Transvaal Lowveld having become progressively depleted and contaminated. Previously perennial rivers now flow as seasonal and even ephemeral systems (Venter and Deacon, 1994). Denudation of the catchment landscape is also resulting in increased sediment production (Van Niekerk and Heritage, 1994). These changes in the flow and sediment regimes of the rivers are leading to morphological adjustments, with associated changes in habitat and water availability for aquatic and riparian fauna and flora. Concerns for the impacts of upstream development on the ecological functioning of the aquatic and riparian ecosystems within the KNP's rivers led to the formation of the multidisciplinary Kruger National Park Rivers Research Programme (see Reid, 1990 and Deacon, 1991). The programme was initiated to establish the ecological water requirements of the rivers flowing through the KNP, so that they may be given due consideration in the planning and management of future resources developments. These needs are both consumptive (primarily transpiration) and non-consumptive (habitat-related) in nature.

Attention has been focused mainly on the Sabie River as the most natural, but imminently threatened, perennial river flowing through the KNP. The Sabie River is characterised by a wide fringe of riparian vegetation colonising the river banks, where more than 130 indigenous species of shrubs and trees occur. The riverine vegetation is not only an essential refuge for fish, reptiles, amphibians, invertebrates and hippopotami, but also provides important habitat for birdlife and browsers that utilise the riparian zone. In the Sabie River this vegetation is susceptible to widespread fatalities and re-distribution resulting from inadequate water supply and river morphology changes due to modified flow and sediment regimes. The future viability of the whole riparian ecosystem therefore depends on ensuring a water supply sufficient to meet the transpiration needs of the riparian vegetation. A project was initiated to establish these needs by estimating the transpiration losses from the Sabie River within the borders of the KNP, and relating them to climatic and river flow conditions. The project integrates the essential components of the riparian water balance, namely the bank storage dynamics, transpiration extraction by common woody riparian species and the abundant reed species *Phragmites mauritianus*, and the river hydraulics. The partitioning of the riparian water balance into component models, and the basic patterns of water movement into and out of a two-dimensional cross-section through the riparian zone, are illustrated in Fig. 2.

The data requirements for developing and verifying the component models, and for practical application of the water balance model, are shown in Fig. 3. The interactions between the three basic components of the water balance are also indicated. River discharge and climatic conditions are the two fundamental input variables that drive the water balance. The river discharge is the primary management variable, with no direct control being administered over the prevailing climate. The physical and biological systems respond to regulated river flows, with a feedback resulting from changes in bank storage dynamics, vegetation water extraction patterns, geomorphological response and riparian forest structure (species composition and distribution).

The transpiration component of the riparian water balance is best modelled using an empirically-based methodology, owing to the morphological heterogeneity, species diversity and spatial distribution of the riparian vegetation in the Sabie River system (Olbrich, 1992). Bank storage dynamics involves the interaction between in-bank groundwater, surface flow in the river channel, evapotranspiration and regional groundwater storage. This component of the riparian water balance can be described by a generalised finite-difference simulation model for the movement of subsurface water in the river banks adjacent to the active channel (Birkhead and James, 1993). Validation of this model for a given physical and biological system requires substantial data pertaining to the system's physical characteristics. These include subsurface flow boundaries, alluvial soil-hydraulic characteristics (hydraulic conductivity, porosity, and water retention capacity), temporal river flow conditions, and the water extraction characteristics (rate and spatial variability) of the riparian vegetation.

Study site locality

The study site was selected to meet accessibility, security, and physical and biological suitability criteria. The Sabie River within the Kruger National Park was examined using 1:10 000 scale aerial photographs taken in 1986, ground photographs, macro-channel cross-section surveys and ground reconnaissance.

Accessibility to the study site from Skukuza rest camp, preferably using non-tourist roads, was an important practical consideration influencing site selection. The reach of the Sabie River upstream of the Kruger Gate entrance to the Park was not considered as it forms the border between the KNP and farming communities, and consequently presents potential problems for the security of expensive monitoring equipment.

A study site with simplified flow boundaries would reduce complexities in model development. Such sites are limited along the Sabie River, which has a mixed bedrock-alluvial channel with a complex morphology (Van Niekerk and Heritage, 1994). Bedrock outcrops occur in the river channel in areas displaying local change in bedrock resistance as a result of lithological and structural variability (Cheshire, 1994). Deposition of alluvial sediments occurs upstream of such bedrock controls in the active channel as a result of the reduced energy gradient and associated channel competence. To facilitate groundwater data monitoring and modelling, the study location should ideally have a simple macro-channel geometry (single thread channel) and relatively deep alluvial deposits with a zone of saturation above the bedrock. Once a generalised deterministic model of the physical processes governing groundwater movement has been developed and tested, it may then be applied to the more complex geomorphological and biological systems found along the Sabie River (bedrock anastomosing, braided channels and vegetated channel bars) and to other rivers.

The biological characteristics required of the study site include the presence of a suite of the large woody riparian species commonly found along the Sabie River, as well as the reed species *Phragmites mauritianus*.

Based on the above practical, physical and biological considerations, a study site on the Sabie River was selected, approximately 5 km upstream of Skukuza rest camp (Figs. 1 and 4). Access to the study site is by means of a well-maintained non-tourist gravel road. The study area is characterised by a single-thread active channel and lateral bar deposit, densely colonised with reeds. The lateral bar deposit within the study area has existed since the earliest aerial photographs taken in 1940. Results of a ground-penetrating radar and surface surveys suggest that the lateral bar is aggrading, with preferential deposition having taken place on the upstream section of the bar (Birkhead et al., 1995). The site was viewed as being particularly suitable as the stability of the active channel bank affords protection during floods. Furthermore, the wide riparian zone allowed the investigation of groundwater movement across a broad macro-channel. The tree species at the study site include *Trichilia emetica*; *Diospyros mespiliformis*; *Spirostachys africana*; *Ficus sycomorus* and *Berchemia zeyheri*.

Data collection

Data required for development of the bank storage dynamics model include the continuous time variation of the groundwater potentials and river stage, periodic values of soil moisture in the unsaturated zone, and delineation of the permeable and impermeable boundaries.

Monitoring system for groundwater and river stage

The finite-difference groundwater model predicts the unsteady phreatic surface profile, groundwater potentials and soil-water contents along a macro-channel cross-section through the riparian zone. These predictions are used to compute the direction of groundwater movement and bank seepage rates. The groundwater responds to changes in river stage, which is one of the basic input variables that drives the two-dimensional groundwater model (Fig. 3). It is therefore necessary to monitor the temporal variation of river stage at the study site to provide model input data, and also to record the responding groundwater potentials for comparison with modelled predictions.

Electronic pressure transmitters were installed for groundwater and river stage levels. Alternative instrumentation such as float systems linked to chart recorders or shaft encoders and indirect electronic ultrasound depth measurement devices, was considered unsuitable for multiple location monitoring in this ecologically sensitive environment because of inappropriate installation requirements and high costs. Pressure transmitters were favoured over other electronic instruments, such as vibrating wire transducers, because of their wide use locally, favourable installation

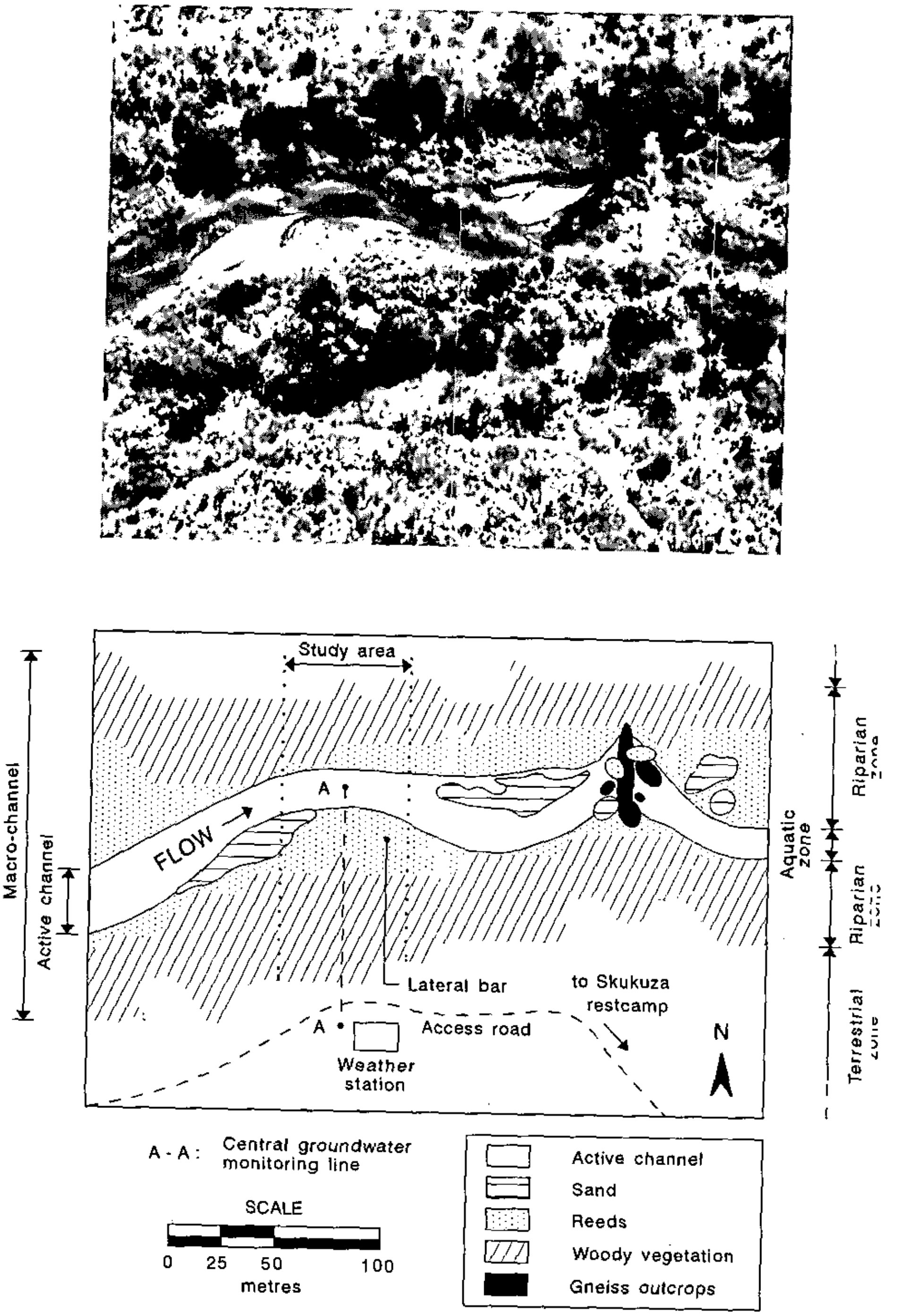


Figure 4
Aerial photograph and diagram showing the study area, riparian vegetation composition, geomorphological features and access to the study area

requirements, ability to tolerate severe environmental conditions, and suitability to the application of monitoring fluid pressure at multiple locations with a single recorder. The pressure transmitter used consists of a stainless steel body and a length of cable lead housing a three-wire system and a venting core that maintains atmospheric pressure at the instrument. The transmitter utilises a semiconductor pressure sensor, the specific resistance of which varies proportionally to the pressure applied by the fluid to the silicon membrane of the sensor.

The groundwater monitoring system installed within the study area comprises a two-dimensional horizontal grid of measuring points (Fig. 5). The central (C) monitoring line consists of a set of five measuring points, spaced at 12.5 m intervals from the low-flow active channel bank to the foot of the macro-channel bank. Monitoring points on the central line measure the groundwater potentials in a lateral (transverse) direction. Three of the measuring points on the central line (3, 4 and 5) consist of two nested piezometers positioned at different elevations to measure the vertical components of flow within the bank. The upstream (U) and downstream (D) lines of three measuring points each are set 20 m off the central line, constituting a grid of measuring locations. The system also allows any local depressions in the groundwater potential arising from localised water extractions by large trees to be measured. The majority of the system's components are installed below ground level to prevent animal disturbance and visual detection.

The height difference between two nested piezometers must be maximised to detect vertical flow gradients. The observation hole should therefore extend to bedrock for placement of the lower piezometer tube. Observation holes for piezometer placement were hand-augered with a 75 mm dia. auger head. This method gave good sample recovery of sediments up to 40 mm dia. The sides of the augered observation holes were self-supporting to the depth of the phreatic surface. The change from cohesive to non-cohesive sands occurred at the phreatic surface, resulting in collapse of the observation hole with no additional increase in depth. To prevent collapse in the zone of saturation a temporary casing was driven ahead of the auger head. This enabled sediment recovery to a maximum depth of 0.75 m below the phreatic surface, which was insufficient for extension of the observation holes to bedrock level.

The piezometer tubes were constructed from galvanised steel conduit rather than polyvinyl chloride (PVC) conduit to provide protection against lightning for the pressure transmitters suspended in the piezometers. The lightning protection to the pressure transmitters provided by the conducting sheath is a more important consideration than the non-corrosive qualities of PVC. The pressure transmitters contribute a considerable proportion of the overall costs of the monitoring equipment (nine pressure transmitters constitute 50% of the total expenditure on equipment for the monitoring system), and it is therefore imperative to incorporate protective features in the design.

A piezometer consists of a length of conduit with a tip connection at the base and the upper end protected with a steel access cap at the ground surface (Fig. 6). The cap provides access to the piezometer for installation of pressure transmitters, on-site calibration and general maintenance requirements. The access cap is cast into concrete with a small section of the cap protruding above ground level. This design feature prevents interference by large animals utilising the riparian zone, particularly elephants and hippopotami, and also limits flooding disturbance. The function of the tip placed at the bottom of the piezometer is to allow the free flow of groundwater between the alluvium and the piezometer tube. The design of the tip is based on the Casagrande-type piezometer tip described by Clark (1988). The piezometer tip is a 40 mm dia. conduit with 3 mm wide slots cut into opposite sides over a length of 200 mm. The tip is covered with a stainless steel mesh (200 µm aperture) which is clamped onto the slotted end (Fig. 6). Gravel packs were placed around the piezometer tip in the observation hole to ensure good connectivity with the surrounding alluvial groundwater reservoir. Bentonite clay seals were used above and below the piezometer tips to prevent vertical flow in the packed and backfilled observation hole. The level of water in the piezometer therefore represents an averaged piezometric potential over the height of the piezometer tip.

The cables from the transmitters are connected at a series of junctions to a cable network that connects the transmitters to the data recorder (Fig. 7). The cable network also carries venting access to each of the transmitter venting tubes. The cable and venting network is a modular system, which facilitates the relocation of pressure transmitters at different monitoring locations within the study area. Steel conduit and junction boxes are used throughout the network to provide lightning protection and are installed below ground level to deter animal disturbance. The automatic recorders (loggers) are housed in a robust steel box above the macro-channel bank (Fig. 5).

The main components of the automatic water level measurement, recording and power supply systems are given in Table 1.

A compromise must be made between range and accuracy when selecting a pressure transmitter, as accuracy decreases with increased range of measurement. The selected transmitter has a range of 0 m to 4 m water head (0 kPa to 40 kPa), with a corresponding accuracy of 0.25% of the full-scale range (10 mm water head). The transmitter has a pressure safety limit of 1.2 bar, allowing it to be subjected to water levels of up to 12 m before any permanent damage results. This represents a flow discharge at the

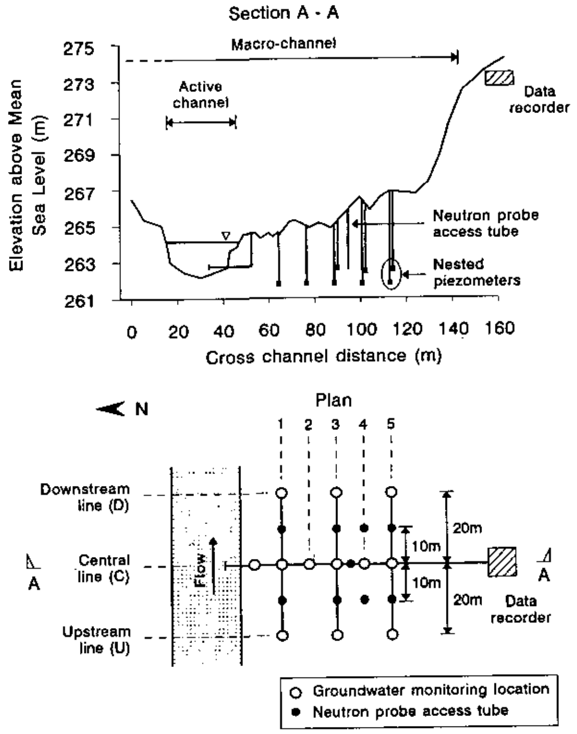


Figure 5
Layout of the groundwater monitoring system at the study site

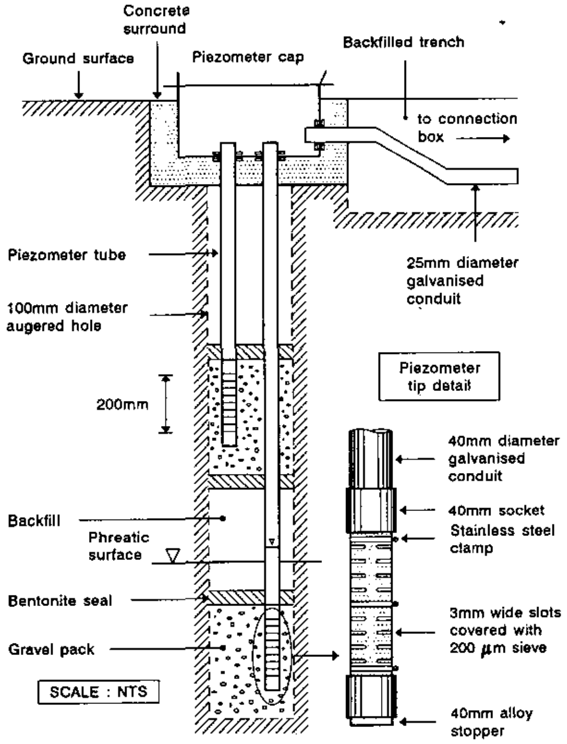


Figure 6
Design of two nested piezometers at a monitoring location, showing piezometer tip detail

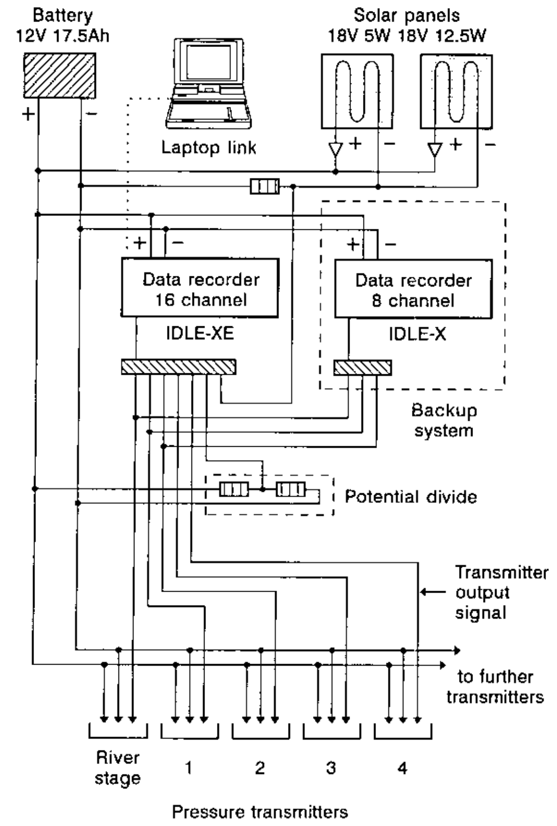


Figure 7
Cable network for connecting the pressure transmitters, data recorders, power supply and laptop link

TABLE 1 INSTRUMENTATION USED FOR THE MEASUREMENT AND RECORDING OF WATER LEVELS AND FOR POWERING THE MONITORING SYSTEM		
	Units	**Instrumentation**
Water level measurement	9	WIKA model 891.13.530 0-20 mA 0-40 kPa pressure transmitter
Automatic water level recording system	1 1	16 channel (analog & digital) DDS IDLE-XE data recorder 8 channel (analog & digital) DDS IDLE-X data recorder
Power supply to monitoring system	1 1 1	12 V 17 Ah/20 h lead acid battery 18 V 5 W solar panel 18V 12.5 W solar panel
Trade names have been supplied to provide specific information on the instrumentation used and do not constitute endorsement by the authors, their respective organisations, or funding agencies.		

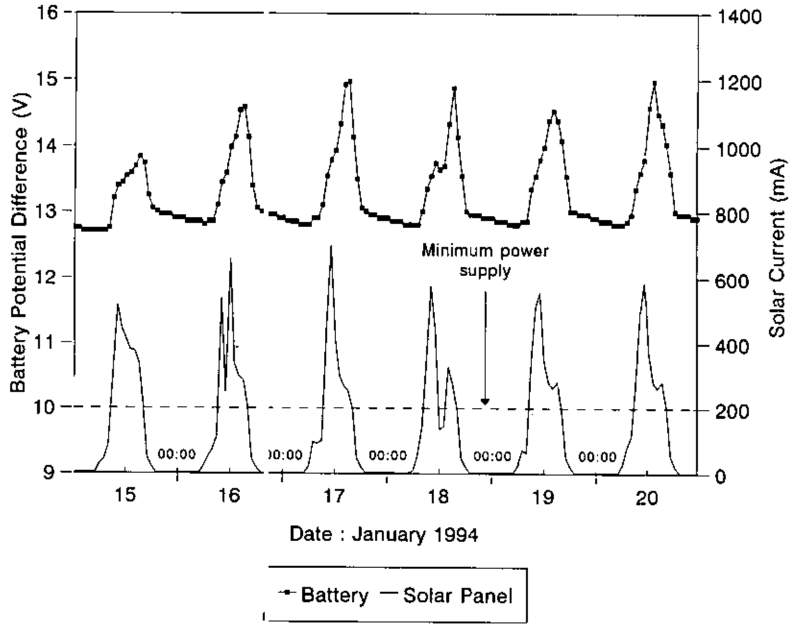


Figure 8
Plot of daily variations in the battery potential difference and solar charge from 15 to 20 January 1994

study site of approximately 1 500 m³/s, which is an extreme flood event.

The pressure transmitters require a power supply in the range 10 V to 30 V. This is supplied by the external battery which is charged by two solar panels (Fig. 7). The solar panels are positioned beyond the riparian forest canopy to prevent shading, particularly during winter. In addition to the transmitter outputs (piezometric potentials), the potential difference across the battery and the current produced by the solar panels is also recorded. The potential difference is measured using a potential divide, and the solar current is calculated by measuring the voltage drop across a resistor. This allows the adequacy of the power supply to the measuring and recording systems to be monitored, and provides useful information for diagnosing the periods and causes of electronic malfunctions. Typical plots of the hourly recordings of the battery potential difference and solar current are presented in Fig. 8. The battery is fully charged at 12.8 V, with the increase above this level representing the static voltage produced by solar charge. This static charge falls rapidly when the battery discharges through the monitoring circuits at night. In the absence of solar power, the monitoring system will operate for a minimum of four days with each of the nine transmitters drawing the maximum current (20 mA per transmitter) at the pressure limit of the instruments (4 m water head). The solar panels are designed to produce 0.97 A when operating under optimal climatic conditions.

The data recorders can be linked to a computer, providing an efficient method of programming the recorder parameters and downloading data. The parameters and recorded data are stored on a removable random access memory (RAM) pack, which may be exchanged in the field or downloaded on site onto disk storage using a laptop computer (Fig. 7).

The river stage monitoring facility consists of a horizontal inlet pipe connected to a vertical stilling well, which is protected at the surface with an access cap (Fig. 9). The inlet is covered with a 200 μm aperture sieve to prevent silt intrusion, while allowing

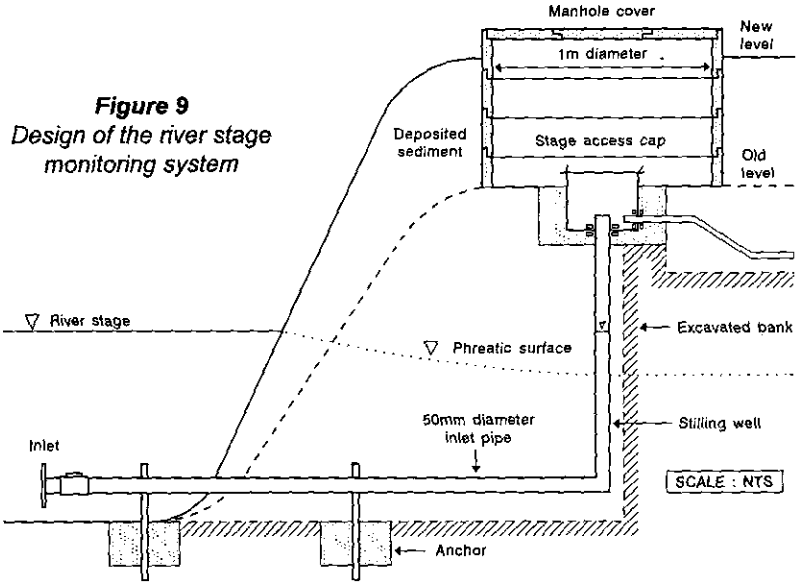


Figure 9
Design of the river stage monitoring system

rapid response of water in the stilling well to stage fluctuations. The access pipe is positioned directly above the active channel bed to allow the measurement of shallow flow depths. A pressure transmitter is suspended in the stilling well and connected to the wiring and venting network in the same way as those for the groundwater monitoring system (Fig. 7). The deposition of sediment over the lateral channel bar during flood events in November 1992 and March 1993 prompted the installation of manhole pipes to gain access to the buried stage access cap (Fig. 9).

Details of the design, installation and operation of this monitoring system are described in full by Birkhead (1994).

Monitoring soil moisture in the unsaturated zone

Soil moisture contents in the unsaturated zone are monitored using a neutron probe. This has been shown to be an effective and convenient means of measuring soil moisture at various depths in a soil profile (Cuenca, 1988). Eight aluminium access tubes were installed within the study area for this purpose, on either side of the central groundwater monitoring line at Locations 1, 3, 4 and 5 (Fig. 5). An additional access tube was installed midway between groundwater monitoring locations C3 and C4 (C3-4) for comparison of neutron probe data with gravimetrically determined soil water contents of augered samples. This comparison is necessary to establish the accuracy of neutron probe data at the study site, where the fluvial deposits are highly stratified and variable, ranging from clays and silts to coarse sands and fine gravels. Because of the time and difficulty involved in extracting samples for water content measurements in non-cohesive dry sands, only this one location (C3-4) was used for comparison. The results obtained have provided sufficient information for calibration of the neutron probe and given indications of the temporal and spatial intensity of data collection required for this purpose.

Delineating groundwater flow boundaries

To model the groundwater flow it is necessary to map the spatial variability and the types of flow boundaries present in the macro-channel. The fluvial sediments at the study site are deposited over gneiss bedrock, which forms the lower groundwater flow boundary. This lower boundary is considered impervious relative to the high saturated hydraulic conductivities of the coarse fluvial sands ($K_s \sim 10^{-1}$ cm/s). Physical probing techniques and ground-penetrating radar (GPR) surveys were conducted to establish the bedrock profile below the coarse sandy sediments constituting the lateral channel bar deposit (Birkhead et al., 1995). The survey demonstrated that GPR is an effective sedimentological tool for accurately delineating bedrock topography beneath coarse fluvial sediments.

Results and discussion

River stage and groundwater levels are being monitored continuously and recorded at hourly intervals. Preliminary results and interpretations are presented here to demonstrate the response of the groundwater to river stage fluctuations. The recorded river stages have also been used to develop a stage-discharge relationship for the site. The soil moisture data collected to date have been used to calibrate the neutron probe and to describe the vertical soil moisture profiles.

Groundwater response

The response of the piezometric potentials at monitoring locations C1, C3 and C5 (at the lower nested piezometers) to a 0.20 m fluctuation of river stage are plotted in Fig. 10. As expected, the rise and fall in river stage is replicated by the groundwater levels, with peak attenuation and lag increasing with increasing distance from the active channel. Similar response characteristics were reported by Beaudry (1989) in the study on the Skeena River floodplains. The rapidity of the response of the groundwater potentials at the study site reflects the high saturated hydraulic conductivities of the coarse sediments.

The recorded piezometric potentials have been used to compute the seepage gradient into the river bank (Fig. 10 inset). It is interesting to note that recharge to the bank from river flow occurs during the entire period of data presented, with no return discharge to the river during the falling stage. For a two-dimensional inflow-outflow situation, with no losses through transpiration or deep percolation to regional aquifers, the volume of water recharged during a rising stage must equal the volume discharged during the subsequent falling stage. Preliminary transpiration investigations show that the discrepancy cannot be accounted for by transpiration, and there is no evidence of significant loss to deep aquifer storage. Observed longitudinal gradients of recorded piezometric levels

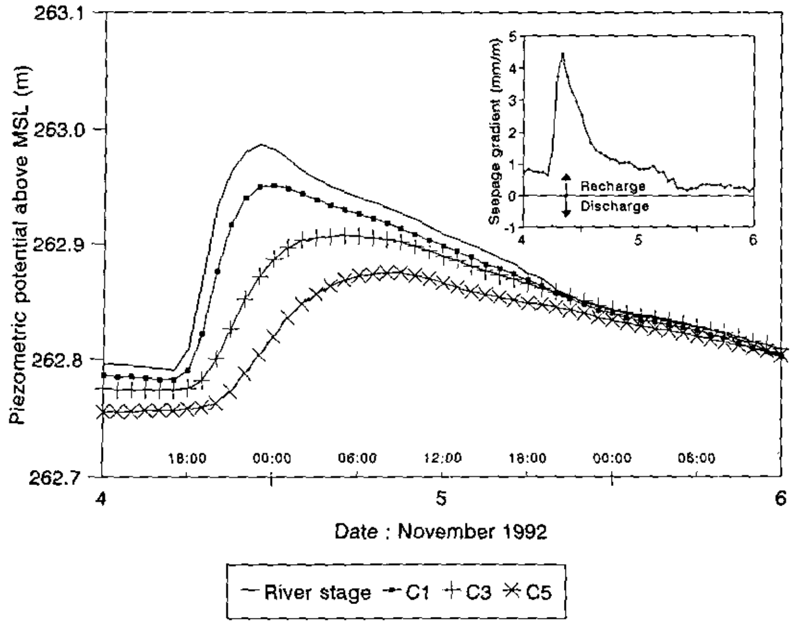


Figure 10
Response of the piezometric potentials to a fluctuation of river stage

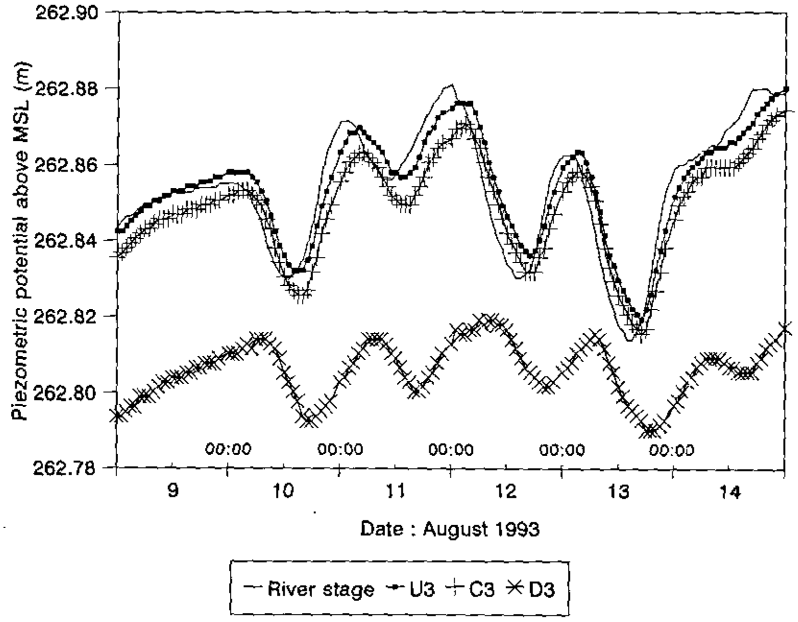


Figure 11
Daily fluctuations of the river stage and piezometric potentials

(such as can be inferred from the offsets between the upstream, central and downstream levels in Fig. 11) confirmed the existence of significant groundwater flow parallel to the river. The longitudinal flows arise from a combination of hydraulic controls (bedrock outcrops) in the active channel immediately downstream of the study area (Fig. 4), and uneven bedrock topography within the bank. The occurrence of longitudinal flows resulted in the extension of the finite-difference groundwater model to quasi-three dimensions.

The river stage fluctuates daily in response to evapotranspiration losses and abstractions for agricultural, industrial and domestic water supply (Fig. 11). The fall in piezometric potentials from approximately 08:00 to 16:00 corresponds with the daytime extractions of groundwater to support transpiration and evaporation losses from the open water surface. The daily river stage fluctuations resulting from these losses are superimposed on the unsteady river discharges determined by the natural hydrology as modified by upstream abstractions and return flows. The event-related fluctuation monitored in Fig. 10, masks the effects of daytime evapotranspiration losses.

Rating curve

The river stage (a fundamental input to the groundwater model) may be determined from the discharge rate (Fig. 3) by using a rating curve (stage-discharge relationship), which may be synthesised or measured directly. The data necessary for defining the rating curve are being measured for the study site. A gauging weir (Station X3H021) is located approximately 5 km upstream of the study site, and no major tributaries join the Sabie River in the intervening reach. The peaks and troughs on the stage and discharge hydrographs have been used to construct a relationship between the stage at the study site and the discharge at the weir (Fig. 12). The attenuation of hydrograph peaks is neglected, and data for periods of substantial rainfall in the subcatchment between the weir and study site have been ignored. This method for characterising the rating curve is useful, since it precludes the need to measure discharge rates at the site during high-flow events, and in a potentially hazardous environment.

Water contents profiles

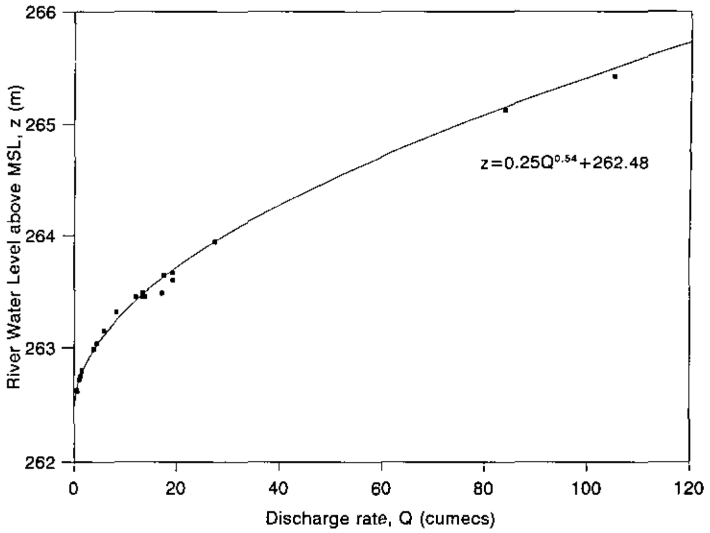
The change in soil water status at monitoring location C3-4 (Fig. 5) during the period November 1993 to March 1994 is given in the water content and neutron count profiles plotted in Figs. 13 and 14 respectively. The neutron count is expressed as the ratio of the neutron meter reading to the standard instrument count Soil samples were taken at 50 mm to 100 mm depth intervals (Fig. 13). The variability in water content with depth reflects the horizontal stratification within the fluvial deposit. The peak water contents (above the capillary fringe) are associated with fine grain-size sediments (clays and silts) that exhibit high water retention capacities. Conversely, the sustained low water contents at a depth of 1 000 mm occur within a poorly graded, medium grain-size sand layer. The positions of high and low water contents are constant with time, except at a depth of 2 000 mm. The change in volumetric water contents here from high (1993-11-08) to low (1994-03-01) is attributed to a change in the sampled sediment type, as auger samples are taken from different radial positions around the neutron access tube. Augered samples were extracted beyond the zone of influence of the neutron probe.

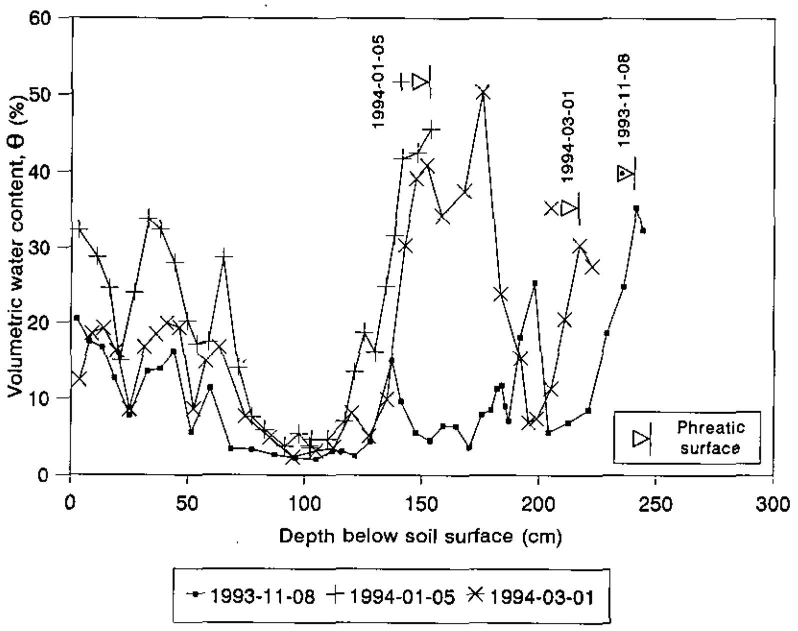
The observed fluctuation in water contents near the soil surface (0 mm to 800 mm) is caused by the

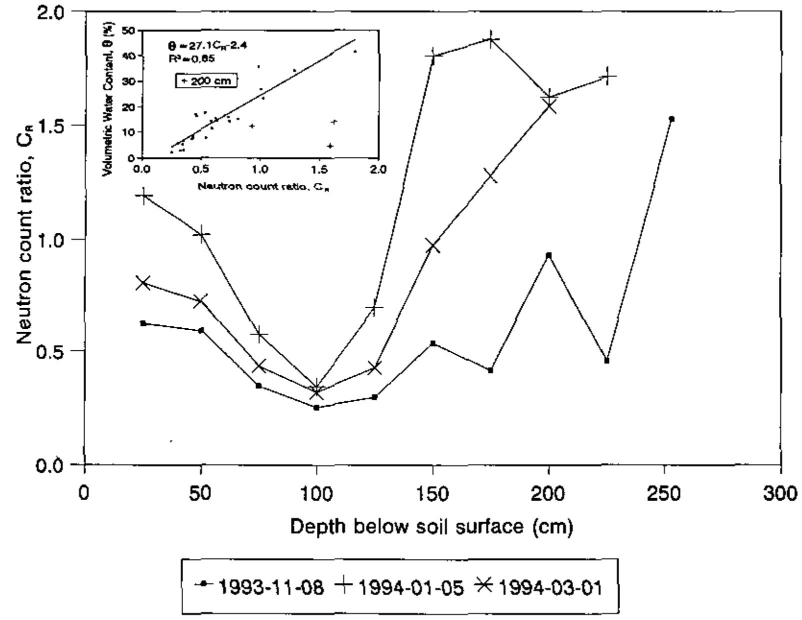
Figure 12 (top)
. Study site-weir rating curve

Figure 13 (middle)
Gravimetrically determined water content profiles

Figure 14 (bottom)
Neutron probe water content profiles







combined effects of rainfall infiltration, evaporation and transpirational water extractions. The sediment layers between depths of 1 200 mm and 2 500 mm experienced an increase and subsequent decrease in water contents due to a fluctuating phreatic surface (Fig. 13). Sustained low water contents at a depth of 1 000 mm infer a low hydraulic conductivity in this layer during the period of measurement. The hydraulic conductivity of a poorly graded material reduces rapidly as the water content falls below saturation, or as the soil water suction rises above the bubbling pressure (height of the capillary fringe) (Bear and Verruijt, 1992). It is therefore deduced that no significant vertical flows (percolation of infiltrated rainfall or capillary rise from the saturated zone) were transmitted across this sandy layer.

Neutron probe measurements were taken at 250 mm intervals (Fig. 14). The neutron probe data exhibit the same spatial and temporal variations in soil water status as the gravimetrically determined water content profiles. The probe data provide a more averaged measure of the spatial variability due to the larger spherical zone of measurement inherent in the technique. Figure 14 (inset) is a plot of the neutron probe data against the water contents measured from sampled sediments. The water contents are expressed per unit volume of soil sample and are averaged over 250 mm depths to coincide with the neutron probe measurement positions. The data correlate well, showing no detectable distinctions between the different measurement depths, with the exception of data collected at a depth of 2 000 mm. The deviation of these data is attributed to errors introduced by auger sampling at spatially isolated locations, and is not included in the regression analysis. The calibration equation is significant in describing soil moisture contents (R^2=0.85, $p<0.001$) and gives a standard error of 4.06% in the prediction of the spatially averaged volumetric water contents from neutron measurements. These results support the use of the neutron probe to estimate the volumetric water contents within the stratified fluvial deposit, using a single calibration relationship for layers with different characteristics (sediment grain-size, bulk density and organic matter contents). This is useful, since it is not feasible to describe the spatial variability in these parameters accurately over the study area.

Conclusions

The design of a monitoring system to collect specific high quality data from a site on the Sabie River for the verification of a computational bank storage dynamics model is described. Data collection problems in the research environment such as flooding, sedimentation and animal disturbance are considered in the design.

Continuous monitoring of river stage and phreatic surface levels enables the response of bank storage to river flow to be understood and the influence of transpiration loss to be appreciated. This facilitates the design of the transpiration soil-moisture interface applicable to modelling bank storage dynamics within the Sabie River system. An analysis of seepage gradients showed the existence of significant longitudinal groundwater flow at the study site, and has resulted in the extension of the finite-difference model to three-dimensions.

The temporal and spatial variations of moisture contents in the unsaturated zone have been measured by neutron probe and by laboratory analysis of field samples. The neutron probe is shown to provide an effective and reliable means of monitoring soil moisture variations in a heterogeneous fluvial deposit, and a simple calibration relationship has been developed for these conditions.

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