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Establishment of a catchment monitoring network through a participatory approach in a small rural catchment in South Africa

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Abstract

The establishment of a catchment monitoring network is a process, from the inception of the idea to its implementation, the latter being the construction of relevant gauging structures and installation of the various instruments. It is useful that the local communities and other stakeholders are involved and participate in such a process as was realised during the establishment of the hydrological monitoring network in the Potshini catchment in the Bergville district in the KwaZulu-Natal Province in South Africa. The paper illustrates the participatory application of various methods and techniques for establishing a hydrological monitoring network, in a small rural inhabited catchment, to monitor hydrological processes at both field and catchment scale for research purposes in water resources management. The authors conclude that the participation of the local community and other stakeholders in catchment monitoring and instilling the sense of ownership and management of natural resources to the local communities needs to be encouraged at all times. Success stories in water resources management by local communities can be realized if such a process is integrated with other development plans in the catchment at all forums with due recognition of the social dynamics of the communities living in the catchment.

1 Introduction

Sound decision making for water resources and environmental management has to be based on good knowledge and factual information regarding the dominant hydrological processes, together with bio-physical characteristics of a catchment and in combination with socio-economic aspects. Such information can only be obtained through establishing networks that are capable of monitoring such hydrological processes at different temporal and spatial scales. The establishment of a catchment monitoring network involves a process, from inception of the idea to the actual construction of the various structures and installation of the necessary equipment and instruments while engaging relevant stakeholders. Such a process is normally driven by a motive to meet certain research objectives (e.g. Wigmosta and Burges, 1997; Gilvear and Bradley, 2000; Hodgson et al., 2002; Ireson et al., 2006), considering the cost implications with regard to construction and acquisition of the various instruments and their maintenance. However, research catchments are typically established in areas where people do not live. In fact, people are usually excluded from such catchments as they add uncontrollable variables to the experiment as well as the risk of theft and vandalism. In this paper we report on the establishment and installation of various instruments and structures for a detailed catchment monitoring network that took place in the midst of a rural community. This provides a good case study for considering the many issues and challenges (social, scientific and engineering) that need to be addressed in the process of establishing the monitoring network in a populated rural catchment in a developing region. There are few case studies in the available literature on the establishment of detailed catchment monitoring networks through a participatory approach involving the local community and other stakeholders. A survey study by Loreta et al. (2006) indicated the desire by local communities and other stakeholders to be involved in water quality monitoring and surveillance in the Mzingwane catchment in Zimbabwe, even though they were not aware of the existence of such a monitoring programme in their locality. However, the participatory approach in catchment monitoring has long term benefits including the opportunity for the relevant stakeholders, notably the local community, to gain insight into the hydrological regime of their locality. This in turn provides a better basis for decision making for farming activities and understanding the impact of anthropogenic activities on water resources in the catchment. Thus, a participatory approach requires a constant effort to initiate a learning process, through which the local community is able to appreciate and recognize the importance of catchment monitoring, not withstanding the willingness of the community to participate in the monitoring exercise.

The Potshini catchment, a small headwater catchment on the foothills of the Drakensburg mountains in South Africa, is inhabited by the Potshini rural community and whose main economic activity is smallholder farming and livestock keeping. As highlighted above, the inclusion of people in research catchments has many challenges. Nevertheless, one can not carry out convincing studies on the interaction between water resources and food security of any rural community without considering the livelihoods of the rural community and the dominant hydrological processes. It is on this understanding that the Potshini catchment monitoring network was established with various objectives as discussed below.

2 Objectives for establishing the Potshini catchment monitoring network

The Potshini catchment monitoring network was established to fulfill a threefold mission in line with the overall objective of the Smallholder System Innovations in Integrated Watershed Management (SSI) research programme (Rockström et al., 2004) of addressing the challenges of increasing food production, improving rural livelihoods while safeguarding critical ecosystem functions and services. The threefold mission encompassed:

- Monitoring the hydro-climatological processes of the Potshini catchment in order to gain an in-depth understanding of the hydrological regime of the catchment and investigate the hydrological and ecosystem impacts of adoption and adaptation of water use innovations (rainwater harvesting) in the Potshini catchment,
- Establishing a capacity to assess, monitor, and manage water and environmental resources in the Potshini community in collaboration with various stakeholders through training on the basic methodologies of catchment monitoring,
- Providing an opportunity for future and further research through the establishment of a catchment monitoring network with a potential for upscaling and integrating into other larger networks in the country. This is due to the fact that the network comprises several permanent structures which other researchers may use in their studies in future after the accomplishment of the SSI research programme.

The SSI research programme is focused on investigating the potential of small-scale water system innovations (e.g. rainwater harvesting, conservation tillage etc.) for upgrading rainfed farming in semi-arid agro-ecosystems, including aspects such as the need for local adaptations of these techniques, adoption of them among smallholder farmers and possible trade-off between water for agriculture and water for surrounding ecosystems. However, it must be noted that SSI is a scientific programme and as such is dedicated to delivery of innovative and high quality research, albeit in a developmental setting. The instrumentation which forms the Potshini hydrological monitoring network ranges in sophistication from simple manually recording rainguages, to state of the art instruments such as a Large Aperture Scintillometer and Electrical Resistivity Tomography instruments.

The process of establishing the Potshini catchment monitoring network was initiated in early 2004 under the SSI research programe (Rockström et al., 2004) at the School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal. The process integrated two approaches (i) a participatory approach where the local community and other stakeholders were involved and participated (ii) a scientific approach which entailed the application of scientific and engineering principles in designing, construction and installation of various structures and instruments. It should be noted that the two approaches were not treated separately but rather formed an integrated continuous learning process where the relevant stakeholders and researchers made an effort to interact and to learn from each other. The main stakeholders for the SSI programme in the Potshini catchment, at various degrees of participation, included the following (i) smallholder farmers actively participating in various experimental and monitoring activities (ii) members of the local community in the Potshini catchment in observation and construction (iii) smallholder farmers neighbouring the Potshini catchment in attending field days and learning sessions (iv) Neighbouring large scale commercial farmers in participating and supporting the catchment monitoring initiative (v) the traditional and local leadership in assembling and motivating the community (vi) the Provincial Department of Agriculture and Environment in supporting teaching, providing material inputs, organizing field days and encouraging the community to become involved (vii) Agricultural Research Council-Institute of Climate Soil and Water in expertise from past research (viii) the Local Authority – the Okhalhamba Municipality in encouraging the community to become involved and providing material inputs (ix) the Department of Water Affairs and Forestry in providing monitoring and domestic boreholes.

The Potshini catchment monitoring network comprises gauging structures and instrumentation, mostly automated, for measuring and monitoring stream flows, overland flow from experimental runoff plots, sediment load, shallow and deep ground water tables, subsurface resistivity using Electrical Resistivty Tomography (Loke, 2003), isotopic composition (Deuterium and Oxygen-18) in both surface and subsurface water, volumetric soil moisture content, soil hydraulic parameters, crop transpiration rates and meteorological parameters. The application of scintillation techniques (Large Aperture Scintillometer) in estimating total evaporation in the Potshini catchment forms an intermediate observation and a calibration scale for remote sensed estimates of total evaporation from satellite images in the catchment and the Thukela river basin at large, using the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a, b; Bastiaanssen, 2000). Preliminary results on hydrological studies based on data obtained from the Potshini catchment monitoring network are reported in Kongo and Jewitt (2006).

2.1 Overview of a logical hydrological measurement sequence

Although hydrological processes vary continuously in time and space, they are often described and derived from point measurements. The resulting data form a time series, which are typically subjected to further processing, including statistical analysis and or hydrological modelling. Chow et al. (1988) highlighted a sequence of logical steps (Fig. 1) which are commonly followed for hydrological measurements and monitoring, beginning with the instrumentation of a physical device that senses or reacts to the physical phenomenon and ending with the delivery of data to the user. Such a sequence was adapted during the establishment of the Potshini catchment monitoring network with an additional participatory component where the input from the local community and other stakeholders was sought and incorporated as indicated in Fig. 1. In the absence of the participatory component, the sequence describes a scenario which is biased to understanding the hydrological processes in a catchment but void of the social dimension of how the local community understand and respond to the hydrological processes being monitored. The social dimension comprises several elements, including the understanding of the knowledge base of the rural community with regard to rainfall patterns, stream flows, temperatures etc, as well as the willingness of the community to learn about and quantify the various hydrological processes taking place in their midst and the importance of understanding such processes. Such an approach perpetuates a sense of ownership and imparts management skills of natural resources to the local community and hence ensures the security of the various installations comprising the catchment monitoring network. The social dimension can be complicated if several stakeholders with diverse interests are involved in the establishment of a catchment monitoring network. Nevertheless, such diversity can be a source of inspiration and strength if a common understanding is sought at the initial stages. However this must be based on good working relationships and trust as was experienced during the establishment of the Potshini catchment monitoring network. Although the steps indicated in Fig. 1 may appear to be obvious, even simple, they need to be followed and documented for the purpose of sharing the experience and knowledge as highlighted in this paper.

2.2 Study area

The Potshini catchment as described in Kongo and Jewitt (2006) is predominantly a smallholder farming area and a sub-catchment of the Quaternary Catchment[1] number

[1]Quaternary Catchments (QC) in South Africa are the smallest delimitations of a river basin upon which policies and decision with regard to water resources management are based upon.

V13D (Emmaus catchment) in the Thukela River basin in the foothills of the Drakensberg Mountains in South Africa. The Thukela river basin is comprised of 86 Quaternary Catchments. The Thukela river basin has an area of 29 036 km^2, while the area of Quaternary Catchment V13D is 285 km^2. Figures 2a and b show an overview of the Thukela river basin and the Potshini catchment. The Potshini catchment comprises 2-nested catchments, with an area of 1.2 km^2(gauged by an H-Flume) and 10 km^2 (gauged by a pressure transducer) respectively. The mean annual precipitation at Potshini is estimated to be 700 mm/a and the estimated mean annual potential evaporation is between 1600 to 2000 mm/a (Kongo and Jewitt, 2006). Due to local topography and high summer rainfall, a good drainage network has developed in the Potshini catchment with most of the streams being perennial and providing water for domestic use to the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream.

3 Methodology

3.1 The participatory process

The research approach applied in establishing the Potshini catchment monitoring network involved Participatory Research, a process where the smallholder farmers and other stakeholders were involved from the initial preparatory stages to the actual construction and instrumentation of the various structures and instruments. Local input was sought regarding the siting of structures and instruments and permission to develop a monitoring network was sought from the local farmer's forum, individual farmers as well as from the traditional and local leaders of the area. A communication process and dialogue was initiated between the researchers and the relevant stakeholders in the catchment. This involved holding meetings with the local leaders (e.g. traditional leaders, Local Government officials, relevant Government Department officials etc.)

The QC were defined and established by the National Department of Water Affairs and Forestry.

and the local community. Local artisans and masons were purposely involved in construction of various structures and installation of some of the instruments as part of a wider learning platform and technology transfer to enable them appreciate the operational mechanisms of the network. The local community continue to be a key stakeholder in the SSI research programme and an ongoing effort is made towards creating and maintaining a cordial relationship with the community based on respect, trust and friendship. The culture and practices (e.g. abstaining from any field activities that involve digging or excavation of the soil during burials) of the Potshini community were respected at all times both during and after the establishment of the Potshini catchment monitoring network. The approach has been proven to be effective in perpetuating a conducive environment for interacting with the local community and hence the goodwill of the community to safeguard any installations in the area. Several smallholder farmers in the Potshini community volunteered to participate in various research activities including managing experimental trials on their farms. The voluntary monitoring of daily rainfall and soil moisture in the catchment by some of the smallholder farmers in the Potshini catchment was beneficial to them especially in determining the appropriate time for planting their single summer maize crop.

3.1.1 Communication and feedback platforms for learning and sustainable adoption

A participatory learning process must involve a feedback mechanism where continuous updating and response are integrated in the learning process. Such feedback mechanisms should accommodate as much as possible, the opinions and ideas from the various stakeholders. In the Potshini catchment, feedback forums were promoted and encouraged for all stakeholders, at the various levels of participation, where the respective stakeholders are continuously updated on the main research findings, progress on data collection and upcoming research activities within a year. It is during such feedback sessions that the respective stakeholders obtained an in-depth understanding of the ongoing research activities, and appreciation of their contribution to the SSI research programme and to understand the vagaries of hydrological processes in their catchment.

A monthly Farmers Forum, established as a communication and management platform for farmers in the Emmaus ward (the administrative ward in which Potshini falls) in the Bergville District under the then Agricultural Research Council's (ARC) Landcare Project, proved to be a useful platform for the researchers, for dialogue with farmers and for other stakeholders in the area. This forum provided an entry point for the SSI team and through it, the researchers were able to outline the objectives of the SSI programme in the area, its implementation and most importantly the usefulness of voluntary participation of farmers in the research programme. The researchers managed to effectively use the farmer-to-farmer learning structures previously put in place by the ARC Landcare project (Smith et al., 2004) for establishing contact with individual smallholder farmers who were willing to participate in the SSI research programme, especially in the catchment monitoring exercise. It is through such forums that a good working relationship between the Provincial Department of Agriculture office in Bergville and the research team were established. Since then, the SSI Programme continued to benefit and enjoy the support of the Bergville Agricultural office and the SSI researchers attend or are represented at relevant Department of Agriculture functions, which provide a forum for all stakeholders and development projects working in the Bergville District on food security, home economics, community resources and the agricultural sector. The research team has been participating in all field days organized by the Department of Agriculture in Potshini and other nearby wards in the Bergville District and likewise, the Department of Agriculture has actively participated and to some extent facilitated some of the field days organized by the SSI research programe in Potshini.

3.1.2 Siting of stream flow gauging structures

The establishment of the Potshini catchment monitoring network involved the initial stage of reconnaissance surveys to gain a general understanding of the catchment before detailed and specific site surveys were performed as per requirements of each structure or instrument. The siting of the streamflow gauging sites and design of the gauging structures in the Potshini catchment involved the application of the local knowledge, scientific and engineering techniques. In particular, the local knowledge on the dominant hydrological processes, historical peak flows and flood prone areas was vital during the design and construction of one of the stream flow measuring structures, i.e. an H-Flume. It is interesting to note that the information obtained from the local community with regard to historical peak flows, e.g. stream flow depth during historical peak flows, was in agreement with results obtained from a modeling exercise using the Soil Conservation Services (SCS) methodology (Schulze et al., 1992) in determining peak floods from the Potshini catchment.

3.2 Estimation of peak discharge using the SCS methodology

Most of the hydraulic structures in streams and rivers (e.g. bridges, culverts, weirs, flumes etc) need to be designed based on the extreme flow events, which can be obtained through a flow frequency analysis or hydrological modeling. The Soil Conservation Services (SCS) methodology, modified for South Africa conditions, for estimating peak floods in small catchments (Schulze et al., 1992), was applied to estimate the peak discharge for selected return periods in the Potshini catchment in an effort to determine the design flow for an H-flume. In the SCS method, the peak discharge for an increment of time *(ΔD)* is defined as:

$$\Delta q_p = \frac{0.2083 \times A \times \Delta Q}{\Delta D/2 + L} \tag{1}$$

Where Δq_p is the peak discharge of incremental unit hydrograph (m^3/s), A is the catchment area (km^2), ΔQ is the incremental stormflow depth (mm), ΔD is unit duration time (h) used with distribution of daily rainfall to account for rainfall intensity variations and L is the catchment lag (h).

The general hydrological and physical conditions in Potshini catchment favoured the use of the SCS lag equation for estimating catchment response time. Dry spells occur

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during winter (May to October) and most parts of the catchment have limited vegetation and mulch cover due to overgrazing and hence the area could be categorized as semi-arid, which suits the application of the lag equation. The SCS lag equation is given as:

$$L = \frac{l^{0.8}(S' + 25.4)^{0.7}}{7069 \times y^{0.5}} \tag{2}$$

$$y = \frac{M \times N \times 10^{-4}}{A} \tag{3}$$

$$S' = \frac{25400}{\mathrm{CN-II}} - 254 \tag{4}$$

Where L is the catchment lag time (h), l the hydraulic length of catchment along the main channel (m), A is the catchment area (km^2), y is the average catchment slope (%), $M$is the total length of all contour lines (m) within the catchment, N is contour intervals (m), A is the catchment area (km^2) and CN-II is the curve number of type II. Table 1 indicates the physical and hydrological parameters for the Potshini catchment used as inputs to the SCS model. The catchment area, number of contours, total length of contours and the hydraulic length of the catchment was determined from a 1:50 000 topographical map covering the catchment while the Mean Annual Precipitation (MAP) was obtained from the nearby Bergville weather station.

Based on previously mapped rainfall intensity distribution types, the location of the catchment coincided with storm intensity distribution type 4 (Schulze et al., 1992). With a coefficient of initial abstraction being 0.1, the catchment lag time was estimated to be 0.58 h (37 min). A summary of the SCS model results is presented in Table 2.

3.3 Design of the H-flume

The most common hydraulic structures that are used for measuring stream flows are weirs and flumes (Ackers et al., 1978). If not well designed, weirs may end up being sediment traps leading to change of the channel geometry (width and depth), which is the main reason why weirs need to be re-calibrated with time. This is not the case for H-flumes. The geometry and design of an H-flume allows for free flow of the stream discharge, save for the constriction at the front end, and hence enabling the implementation of a sediment load monitoring scheme as is the case with the Potshini H-flume. In designing the Potshini H-flume, a 2-year return peak flood was considered i.e. 6.4 m^3/s, although the actual design flow for the H-flume was 3.42 m^3/s. The main reasons for adopting a lesser design flow was the fact that the available stage-discharge relationship for H-flumes, developed by SCS, is only valid for a maximum discharge of 3.42 m^3/s, and it was necessary to use an H-flume rather than a weir in the catchment to facilitate accurate monitoring of the sediment load from the catchment. This is rather difficult to achieve using a weir. Also, low flows were considered important to capture accurately, so a size smaller than that required for the 1:2 year event was accepted. Since this was the largest H-flume calibration available, it was accepted in lieu of complex calibration of an off-spec flume. The design of the Potshini H-flume was based on the criteria outlined by Ackers et al. (1978). The fundamental concern and priority during the design and construction of the Potshini H-flume was maintaining structural stability during and after excessive loading events i.e. peaks floods. The SCS modeling results were used as one of the bases for determining the design flood for the H-flume from which the necessary precautionary features and safety factors were incorporated in the design and construction of the H-flume in an effort to allow the safe passage of a 2-year return period flood of 6.4 m^3/s without affecting structural stability. Some of the precautionary features included reinforcing the walls of the approach channel with starter bars drilled into the bedrock, anchoring the foundation against sliding and stabilizing the slopes of the stream banks both on the upstream and downstream of the 11 m long approach channel for a distance of 4 m with reinforced rip-rap.

3.4 Streamflow measurements and monitoring of water quality parameters

Streamflow in the Potshini catchment is monitored at two sites coinciding with two nested subcatchments of 1.2 and 10 km^2, respectively, as indicated in Fig. 2. The smaller subcatchment, 1.2 km^2, is gauged by the H-Flume, while the larger catchment is gauged by monitoring water level fluctuations using a pressure transducer installed at a road culvert. The monitoring of the flow rates at the Potshini H-flume is governed by a set of 3 rating equations, each describing a unique stage-discharge relationship for a given range of flow depths. Monitoring of level of discharge in the Potshini H-flume is via a tube, connecting the open channel discharge to a stilling well. In the Potshini H-flume, the approach channel is connected to a stilling well, 4.6 m away, by a 50 mm pipe at the floor level of the approach channel and sloping slightly in the direction of the stilling well. With this set-up, the water level in the approach channel and the stilling well will always be the same and hence makes it possible to monitor the water levels in the approach channel by recording the water levels in the stilling well through the use of a float and a data logger mechanism as illustrated in Fig. 3. The float in the stilling well follows the rise and fall of the water level in the approach channel and such movements are translated into rotational movements through a pulley system on a shaft encoder, which is linked to a data logger. Figure 4 shows the Potshini H-flume in operation.

3.4.1 Monitoring of sediment load and isotopic composition of stream flow

It is always a challenge to obtain a representative water sample in streams at the desired time, for analytical work on water quality. This is compounded by the fact that stream flows emanating from head water catchments of relatively small area in semi arid areas are highly variable, with quick overland flows and interflows. A good sampling scheme should take into consideration such variations of flow by taking frequent samples during changing flow. Water quality, e.g. sediment load, and isotopic composition, e.g. Oxygen-18 and Deuterium (^{18}O and ^{2}H) of stream flow will show less variation at constant flow and hence less frequent sampling is required. The Potshini

H-flume was equipped with an ISCO sampler, with a capacity of 24 sampling bottles of 500ml. The sampler was controlled by a Mike Cotton System (MCS) data logger which recorded the water levels in the stream as described above. The sampling-trigger parameters in the MCS data logger were varied accordingly to achieve an appropriate sampling scheme in which a sample was only taken if the depth of flow changed by 10 mm. For low and high constant flows, the sampling scheme was set to trigger a sampling event after 7 and 3 m^3 of discharge respectively was recorded to have passed the sampling point. The samples were then analyzed for suspended solids and the isotopic composition of ^{18}O and ^{2}H.

3.4.2 Monitoring of stream flow depth using a pressure transducer

The choice of using any of the stream flow gauging structures depends on a number of factors, one being the geometry of the stream channel at the gauging site. For example, in wide channel sections where the construction of a flume or a weir may not be feasible (e.g. due to cost constrains), a cheaper option is to use a pressure transducer to monitor the water levels in the stream accurately and subsequently develop a rating curve for that section after carrying out a detailed survey of the cross-section at the site, applying open channel flow theory and/or conducting flow velocity transects at different discharges. It must be noted that the cross-section must be stable, i.e. not changing with time, for the integrity of the developed rating curve to hold. In the Potshini catchment monitoring network, a pressure transducer together with a HOBO data logger were installed under a culvert bridge approximately 4 km downstream from the Potshini H-flume. Sediment load was not monitored at this site due to the existence of small upstream reservoirs, which in turn trap the sediment load in the stream. The pressure transducer was calibrated by subjecting it to pressure from a gradually increasing column of water, from 0 to 1000 mm while recording the output voltage signal from the transducer. A similar exercise was done for a decreasing water column. The calibration equation for the pressure transducer is as indicated in Eq. (5)

$$H = 13.5307564 + 0.45355129 \times V \tag{5}$$

where H is the stream flow depth (mm) and V is voltage output from the pressure transducer (mV). Velocity transect surveys, at different discharges, were carried out across the culvert bridge using a propeller current meter. The concrete culvert bridge had a regular rectangular shape and hence made it easier to apply the Manning's open channel flow equation and subsequent development of the rating curve. Equation (6) shows the established rating curve at the culvert bridge.

$$Q = 8.267 \times H^{1.6403} \tag{6}$$

where Q is flow rate in m^3/s and H is the stream flow depth (m).

3.5 Climatic parameters

Rainfall is clearly the main parameter that drives the hydrological cycle in a catchment, hence the need to observe its occurrence accurately, both spatially and temporally. Manual raingauges, if well managed, can provide relatively accurate daily rainfall data in a catchment and their affordability, availability and the ease of installation and operation makes them attractive, especially to smallholder farmers. After a reconnaissance survey in the catchment, 8 potential sites (homesteads) were identified in the 1.2 km^2 Potshini catchment for installing manual raingauges. The family members in these homesteads were then approached, beginning with the head of the homestead, to seek permission and the goodwill from the members of the homestead to permit the installation of the manual raingauges and most importantly take daily rainfall readings. A rainfall data recording booklet, translated into the local language – the *IsiZulu*, was given to the identified households to record and keep the daily rainfall records. The smallholder farmers record rainfall twice a day, i.e. at 09:00 and 17:00, from which the total daily rainfall is computed as the sum of the morning and evening readings. Various individuals and households in Potshini participate by monitoring manual raingauges on a daily basis. This promotes the philosophy of participatory catchment monitoring to the Potshini community.

Rainfall data from the manual raingauges were augmented by climatic records from two automatic weather stations installed in the Potshini catchment. Each weather station was positioned near a stream flow gauging station (H-flume and the pressure transducer) at a distance of 4 km apart, in the two nested subcatchments. One of the weather stations was installed in 2005 in the midst of the local community (community weather station) and upstream of an existing telemetric weather station which was operational since 2002 on a nearby commercial farm and managed by the Agricultural Research Council (ARC) of South Africa. A rainfall collector was attached to the automatic raingauge in the community weather station to collect rainwater for analysis of isotopic composition of ^{18}O and ^{2}H. The collector comprised six-400 ml bottles which filled sequentially during a rainfall event. The community members assisted in taking and labeling of the rainwater samples after a rainfall event and emptied the bottles to allow fresh rainwater samples to fill the bottles during a subsequent rainfall event. Since their installation, each of the two weather stations was maintained by the owner of the commercial farm and the local community, respectively. Some of the community members participated in the fencing of the community weather station and maintained tidiness within and on its surroundings. Fencing of the weather station is only meant to safeguard the instrumentation against the cattle which graze freely, especially during the winter season. The security of the weather station is entrusted to the goodwill of the local community, through the traditional leadership of the community and the goodwill generated by the participatory approach. Recording of climatic data in the two weather stations was done at a time step of 15 min and the data accessible to all researchers in the ARC, the SSI programme and any other interested stakeholder.

3.6 Runoff plots

A standard runoff plot, as described by the Soil Conservation Services, measures 22.13 m long with an appropriate width of greater than 2 m on a slope of 9%. Such runoff plots are used in estimating the soil erodibilty factor in the Universal Soil Loss Equation-USLE (Wischmeier and Smith, 1978). One of the research themes in the SSI research programme was aimed at investigating the hydrological processes at field scale (<1 hectare) and hence runoff plots were used for this purpose as controlled micro catchments. Eighteen runoff plots, under different treatments, i.e. agricultural management practices, were installed in three different smallholder farms, on similar slopes, in an effort to carry out water balance studies at the field scale (smallholder farms) and to investigate the influence and impact of different tillage and agricultural practices i.e. water use innovations, on surface runoff generating characteristics in the catchment. The experimental design entailed installing a runoff plot in each conservation agricultural practice (treatment) in the three smallholder farms and monitoring the surface runoff, volumetric soil moisture content, soil hydraulic characteristics, crop transpiration rates, crop phenological properties and biomass production. The 18 runoff plots were designed while taking into account the rainfall intensities in the area. Modified USLE plots were installed with dimensions of 10 m long and 2.45 m wide. Strips of 0.245 m wide galvanized sheet metal were used to demarcate the area of each runoff plot.

A fundamental parameter that had to be determined before the installation of the runoff plots was the general slope of individual smallholder farms. This was done through a leveling survey exercise. A contour map for each field where the runoff plots were to be installed, was created and general slopes estimated. These slopes where found to range from 2–4%. Four sites were identified for the installation of the 18 runoff plots, three of them being managed by smallholder farmers in the catchment. The fourth site was a controlled research site where experimental set up and trials, similar to the farmer managed trials, were carried out in an effort to compare and validate the results from the farmer managed trials. Figure 5 shows a set of runoff plots at the controlled research site in the catchment while Fig. 6 shows runoff plots in a smallholder farmer's field (farmer managed trial).

3.7 Tipping buckets

The flow rate of overland flow from each runoff plot was measured by use of a tipping bucket (Fig. 7), which was calibrated to hold 2 l in each bucket. The knowledge of the rainfall intensities in the catchment was useful in estimating the size of the tipping buckets and subsequent calibration of the tipping volumes. The number of tips was recorded using a HOBO event data logger, secured in a housing (Fig. 7), and linked to a proxy switch which was triggered at each tip. A manual counter was used as a backup data recording device. A small button-magnet was attached to one side of the tipping bucket, while a stationary proxy switch was fixed to the frame supporting the tipping buckets. As the buckets swing on their axis (oiled bearings), the proxy switch detects the changing magnetic field due to the movement of the magnet on the side of the swinging bucket. The proxy switch then sends a logging signal to the data logger. This set up eliminates "double counting" which is due to the rebounding action of the buckets and is often observed when using manual counters.

3.8 Overland flow samplers in runoff plots for water quality analysis

Five runoff plots in one of the experimental sites in the catchment were fitted with semi-automated sediment samplers with the objective of determining the sediment loads from the different agricultural practices under investigation. The sediment samplers consisted of flow splitting containers (flow splitters) and a sample storage tank. The flow splitters, captured the discharge from one bucket during each runoff event. Each splitter, Fig. 7, was fitted with five outlet pipes of which only one pipe drained into a sample holding tank, while the remaining four outlet pipes discharged to waste in a drainage channel. Thus one tenth of the total flow from the runoff plot was captured in the sample tank. After each runoff event, and after vigorous stirring, 500 ml discharge samples were manually taken from the sample tank and labeled by members of the local community for sediment load analysis and composition of stable isotopes of water. Figure 7 shows a flow splitter attached to a tipping bucket in one of the runoff plots in

Potshini. The sample tanks are emptied by the community members after the sampling exercise to allow fresh discharge to drain into the tanks in subsequent runoff events. The design of the sample collection system involved surveying the terrain of the area near the drainage channel so as to determine the excavation depths and computing the required capacity of the sample tanks. A simple approach was used to determine the tank volumes by assuming a runoff coefficient of 0.2 and using the maximum daily rainfall event observed at the site during the prior 10 years (86 mm) and allowing for a 10% freeboard volume.

3.9 Soil moisture profiling

Ongoing monitoring of the volumetric soil moisture in the Potshini catchment was implemented using a Time Domain Reflectometry (TDR) method. This involved inserting a TRIME-T3 probe into 42 mm access tubes, inserted into the soil profile to convenient depths, and taking volumetric soil moisture content readings at different depths. Several methods have been suggested on how to insert these access tubes into the soil and one of them is by pre-boring holes with appropriate soil augers, of relatively small diameter, and inserting the access tubes into the augered holes. This practice was followed in the Potshini catchment. Twenty two access tubes of different depths ranging from 1.2 m to 1.5 m were inserted in various sites in the 1.2 km^2 upper sub-catchment. The access tubes were inserted in all of the runoff plots under different land management practices, notably conservation and conventional agricultural practices. A weekly monitoring exercise for volumetric soil moisture content in the Potshini catchment was then established where readings were taken at 30 cm intervals in all access tubes. The weekly soil moisture data was complimented with data from Watermark sensors, where a nest of three sensors were installed in all runoff plots in the catchment at depths of 30, 60 and 90 cm and attached to a HOBO data logger with a logging time step of 15 min. The Watermark sensors were to provide a continuous and indirect measurement of soil matric potential after a calibration exercise, which entailed subjecting the sensors to known soil moisture conditions.

3.10 Monitoring of shallow groundwater

Subsurface flows constitute an important component in developing a water balance for a catchment. In particular, accumulated hillslope seepage forms a shallow groundwater table which contributes significantly to the total stream flow. It is therefore important to establish its occurrence, direction of flow and possible flow rates. As highlighted in Kongo and Jewitt (2006), the shallow groundwater in the Potshini catchment is monitored via 12 shallow groundwater wells, which were installed through the collaboration and participation of the local community. Since the intensively monitored upper subcatchment (Fig. 2b) is predominantly an agricultural area for smallholder farmers, permission was sought from the local leaders and individual farmers to allow the augering of the 100 mm diameter holes in some of the farms. The holes were drilled, on transects, after a reconnaissance survey. The wells were strategically installed on sites where they would not interfere with the farming activities since most of the farming operations in the area make use of animal and or tractor drawn implements. Two transects, one on each side of the catchment, were identified. The transects were more or less perpendicular to the general slope of the catchment. 100 mm holes were augered to depths reaching the bedrock or confining layer, but not deeper than 3.5 m. 63 mm diameter plastic pipes of appropriate lengths were inserted into the augered holes so that at least 0.4 m length of the pipe protruded above the ground surface. The pipes have thin horizontal slots machined through the pipe over their bottom 0.6 m so that the shallow groundwater level could be recorded in the well. To avoid clogging of the slotted perforations by the fines and clay at the bottom of the wells, a clean (washed) sand screen was packed around the outer annulus of the plastic pipes, covering the perforations to a height of 0.8 m from the bottom of the wells. For each well, the rest of the well's depth was filled with the previously augered soil material save for the top 0.3 m, where cement mortar was cast around the 63 mm plastic pipe before a 0.4 m concrete slab was cast at the top to a level slightly above the ground surface. Such cement and concrete works prevent preferential flows down the external wall of the

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pipe when the soils are saturated during wet seasons. Pressure transducers were then installed in 8 of the shallow groundwater wells, after a calibration exercise, and linked to HOBO data loggers which recorded the fluctuation of the water table at a time step of 30 min. The data loggers and their respective power batteries were secured in metallic safe boxes embedded in concrete to safeguard the data loggers from unfavorable weather conditions. The other 4 shallow groundwater wells were used to sample the shallow groundwater for composition of stable isotopes of water. Table 3 summarises the observation shallow groundwater installation data. The layout of the 12 shallow groundwater wells in the Potshini catchment is as shown in Fig. 2b in a previous section of this paper.

3.11 Monitoring of deep groundwater

Through funding from the Department of Water Affairs and Forestry (DWAF) and in collaboration with the local community, two deep groundwater observation well sites were identified and subsequently sunk in the Potshini catchment. One of the wells (100 m deep) supplied water to the local community for domestic use while the other (120 m deep) is useful for research purposes under the ongoing SSI research programme. It should be noted that DWAF is one of the main stakeholders of the SSI research programme and is supportive of the SSI research themes especially on hydrological studies and institutional development on water resources management. The existing 3 domestic water supply wells (greater than 50 m deep) in the Potshini community, previously sunk by the local authorities, complimented and expanded the spatial coverage of monitoring deep groundwater in the catchment including monitoring for the stable isotopes of subsurface water. The monitoring of the deep groundwater was to contribute towards closing of the gap in defining the various components of the hydrological cycle in the catchment. The continued support and collaboration with the Department of Water Affairs and Forestry facilitated a sustainable monitoring programme of the deep groundwater in the catchment, as part of an ongoing DWAF initiative to monitor groundwater in the larger Thukela river basin (Mkidze, 2006[2]). DWAF was to continue monitoring the deep groundwater in the Potshini catchment after the end of the SSI research programme. Figure 8 shows the borehole log information for the 120 m deep groundwater observation well in the Potshini catchment.

3.12 Electrical Resistivity Tomography (ERT) survey

Geophysical electrical resistivity tomography techniques are non-destructive techniques that provide a pseudo-section of apparent or effective resistivity of the subsurface. These pseudo-sections are then inverted to provide an interpretation of the actual resistivity distribution in a 2-D section of the subsurface. The 2-D Electrical Resitivity Tomography (ERT) surveys in the Potshini catchment was carried out with the objective of characterizing the occurence of subsurface water. The method is useful both as a means of rapid site reconnaissance that can provide information on the subsurface structures and facilitates the extrapolation of observed data, e.g. observed groundwater levels, between observation points. This can only be done where sufficient site correlations have been established between the observed data being extrapolated and the information derived from the geophysical survey. The ERT methodology, as applied in the Potshini catchment, is aimed at augmenting and up-scaling the monitoring of the point-shallow groundwater in the Potshini catchment using shallow groundwater wells to a relatively larger spatial extents and depths. Six transects in the catchment were identified for the ERT survey; 2 of which coincided with the shallow groundwater well transects on the right and left bank of the stream as indicated in Fig. 9. Resistivity surveys were carried out in collaboration with the local community where permission was sought from the local leaders and individual owners of the parcels of land where the survey transects were to pass through. The resistivity meter that was available for this research study was the ABEM Terrameter system with four cables of 100 m long.

[2]Mkidze, S.: Personal communication, KwaZulu-Natal Provincial Department of Water Affairs and Forestry-Durban, 2006.

Most of the smallholder farmers were eager to have the ERT survey transects passing through their farms so that they could get to know the sub-surface profiling of their farms, especially the occurrence of groundwater. In an effort to characterize the hydrological processes in the catchment, the resistivity survey was scheduled to be carried out during the wet and dry season of each year.

During the initial ERT surveys, an electrode spacing of 1 and 5 m was used for mapping shallow (<10 m) and deep (up to 60 m) subsurface resistivites respectively. Each transect was 400 m long and a total of 81 electrodes were used. The Wenner Log protocol, which is sensitive to vertical changes in the subsurface resistivity (Loke, 2003) was used in the survey exercise. It is worthy noting that the resistivity survey was also aimed at identifying potential sites for sinking 2 deep observation groundwater wells in the catchment in collaboration with the Department of Water Affairs and Forestry as described above. The resistivity sections were computed using the RES2DINV software, applying the 2-D inverse numerical modelling technique and optimized using standard Gauss-Newton methods. Relative elevation data for each electrode on each transect was included in the modelling exercise to account for the effect of topography on the occurrence of geological features (resistivities) along the respective transects.

3.13 Monitoring of total evaporation using the Large Aperture Scintillometer

According to Rockström (1999), in semi-arid tropical agricultural areas, direct Evaporation (E) from the surface generally accounts for 30–50% while transpiration (T) accounts for only 15–30% of total rainfall. Total evaporation *(Et)* is highly variable over time and space and any effort towards enhancing the ability to confidently quantify it at large spatial scales is recognized as an important contribution in water resources management. As highlighted in Kongo and Jewitt (2006), the challenge in determining the spatial and temporal variation of *Et* over large areas is compounded by the many factors that influence its occurrence and prevalence and hence make it the most difficult parameter to determine in hydrology. The conventional approaches for quantifying *Et* have been based on localized point measurements which do not allow for flux estimation over large geographical areas. These approaches include direct measurements (evaporation pan, Lysimeters etc.), climatic stations (eddy correlations, Penman, Bowen ratio etc.) and hydrological models (water balance).

The Large Aperture Scintillometer (LAS) is an instrument that measures the turbulent intensity of the refractive index fluctuations of air from the intensity fluctuations of a received signal (Kohsiek and Herben, 1983; Andreas, 1989; Hill, 1992; Cain et al., 2001). This signal is transmitted by a light source placed at a set distance apart (typically less than 10 km). Figure 10 shows the receiver station of the Large Aperture Scintillometer at the Potshini catchment. At the receiver the spatial turbulent intensity is measured as a refractive index structure parameter C_n^2 ($m^{-2/3}$) which can be related to the structure function parameter of temperature C_T^2 ($K^2\,m^{-2/3}$). Additional data on temperature, pressure and humidity are necessary to compute the structure function parameter of temperature which can then be converted to sensible heat flux (Kite and Droogers, 2000). With known net radiation and soil heat flux, the latent heat flux can be computed as a residual in the energy balance equation as indicated in Eq. (7).

$$\lambda E_t = R_n - H - G \tag{7}$$

where λE_t is the latent heat flux ($W\,m^{-2}$), R_n is the net radiation ($W\,m^{-2}$), H is the sensible heat flux ($W\,m^{-2}$) and G is the soil heat flux ($W\,m^{-2}$). The total evaporation can then be computed from the latent heat flux. The measurement of total evaporation in the Potshini catchment using scintillation techniques started in early 2006, though the exercise was interrupted briefly after the LAS was struck by lightning. The installation and siting of the LAS was done in collaboration with the local community in the Potshini catchment. Both the transmitter and the receiver were stationed at homesteads in the community, and the owners volunteered to maintain and protect the respective instrumentation. Nevertheless, it is useful to note that the whole community was involved during the initial stages of installing the LAS through community meetings which were mobilised by the local leadership. As was the case with other installations in the catchment, the goodwill of the community was sought with regard to the safety and security of this state of the art instrument.

3.14 Remote sensing

There are many applications of remote sensing in water resources management including hydrogeologic mapping, landuse change studies, estimation of total evaporation, mapping and monitoring of wetlands etc. The main application of remote sensing in the ongoing study will be the estimation of total evaporation in the Potshini catchment and the Thukela river basin using the energy balance method. The Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a, b; Bastiaanssen, 2000) will be applied and validated in the Potshini catchment and Thukela river basin. As highlighted in Kongo and Jewitt (2006), the SEBAL was initially applied in the Potshini catchment and beyond using Landsat-TM data and more analysis is to be carried out using the freely available satellite data. SEBAL is an energy partitioning algorithm comprised of twenty-five computational sub-models that calculate E_t and other energy exchanges at the earth's surface. The algorithm computes most essential hydro-meteorological parameters from a satellite image and requires limited ground based meteorological data (Farah and Bastiaanssen, 2001). Only incoming solar radiation, air temperature and wind speed data are required. SEBAL estimates E_t as the residual of an energy balance (similar approach as in the scintillation technique) applied to the land surface for each pixel of the satellite image. The application of the scintillation techniques in estimating total evaporation in the catchment forms an intermediate observation and calibration scale for the SEBAL estimates in the catchment and beyond. Table 4 indicates some of the potential satellite data available for the SEBAL analysis in the ongoing study.

4 Conclusion

Catchment monitoring is the fundamental approach to understanding the various hydrological processes in a catchment. Using this understanding, researchers formulate catchment responses which aid in water resources management. The authors have highlighted and underscored the importance of applying Participatory Research techniques in hydrological research studies where other stakeholders are involved. The feedback process where various stakeholders were updated on the research activities including visual interpretation of the data collected from the catchment monitoring network proved to be a useful tool in instilling a sense of ownership to the local community while the other stakeholders appreciated their contribution and participation in the SSI research programme. The experience drawn from establishing the catchment monitoring network in Potshini, a rural community in Bergville District in South Africa, has proved that there are more opportunities and gains (both material and ideas) to benefit from involving other stakeholders. The level and stage of participation of each stakeholder differs but ultimately contributes to the success of such a process. The Potshini catchment monitoring network has several permanent structures and instrumentation which will benefit other researchers for a long period of time. The structures and instruments have been installed in individual farms belonging to willing smallholder farmers in the Potshini community. A number of the farmers have volunteered to monitor some of the hydrological processes and take readings accordingly. The traditional leadership in Potshini agreed to host and support the SSI research programme and the local leaders (elected) facilitated, to a great extent the linking of the SSI researchers to the local municipality officials while the extension personnel from the Department of Agriculture in Bergville District and the ARC-Landcare project in Bergville played a key role in linking the SSI research programme with other similar projects and stakeholders in the Bergville district and beyond. Furthermore we have shown that the participation of a local, relatively poorly educated community in a hydrological monitoring programme need not compromise the quality of the scientific endeavour nor the level of sophistication of the instrumentation used. The participatory process of establishing the Potshini catchment monitoring network has emerged as a positive impact to the local community and other stakeholders with regard to appreciating the research findings and above all, the ability to sustain the goodwill of the local community in safeguarding the instruments and structures comprising the network.

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Table 1. Physical and hydrological characteristics of the Potshini catchment.

Area (km^2)	No. of contours	Total length of contours (km)	Contour interval (m)	Hydraulic length (m)	Slope (%)	MAP (mm)
1.2	7	5.75	20	1400	10.46	675

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Table 2. Summary of SCS model results.

Return period (yrs)	2	5	10	20
Design daily rainfall depth(mm)	59	81	98	117
Computed curve number	74.5	74.5	74.5	74.5
Runoff depth (mm)	18.4	32.8	45.2	60.0
Runoff volume (thousand m^3)	20.27	36.09	49.75	66.05
Peak discharge (m^3/s)	6.4	11.6	16.2	21.6

Table 3. Summary of the eight observation shallow groundwater installation characteristics.

Well ID	Position from the stream	Column of water during installation (m)	Total depth of the shallow groundwater well (m)	Altitude (m a.s.l.)	Soil textural class
PRB1	1st, right bank	2.12	3.22	1308	Sandy loam
PRB2	2nd, right bank	1.98	3.32	1312	Clay loam
PRB3	3rd, right bank	1.24	2.84	1316	Loam
PRB4	4th, right bank	0.63	3.38	1324	Loam
PLB1	1st, left bank	2.06	3.32	1307	Sandy loam
PLB2	2nd, left bank	1.86	3.46	1313	Loam sand
PLB3	3rd, left bank	2.1	3.41	1315	Loam
PLB4	4th, left bank	2.08	3.38	1328	Sandy loam

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Table 4. Satellite data for SEBAL analysis in the Potshini catchment.

Imager	Temporal resolution	Spatial resolution (m)	Archive data	Availability
Landsat – TM	8 or 16 days	30	Since 1982	Classified
MODIS	Daily	250, 500, 1000	Since 1999	Free
ASTER	15 days	15	Since 1999	Classified
NOAA(AVHRR)	Daily	1000	Since 1980	Free

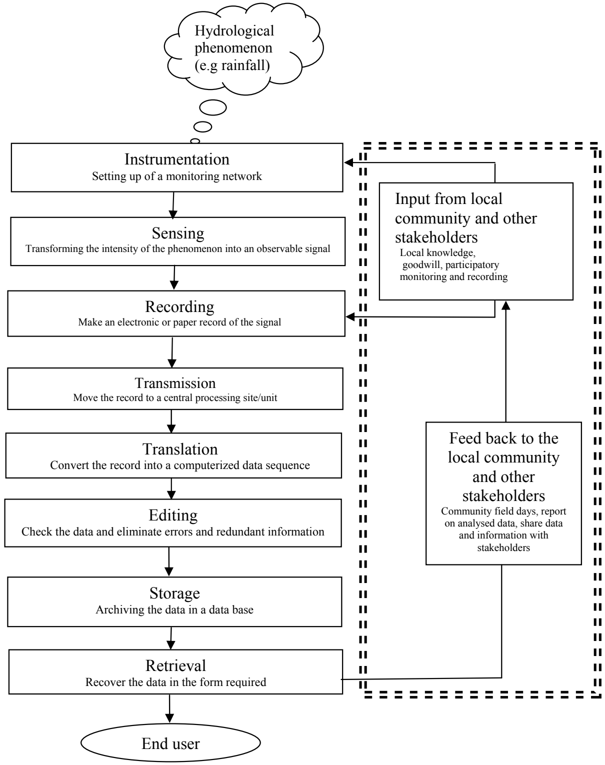

Fig. 1. Hydrological measurement sequence (adapted from Chow et al., 1988) with an additional participatory component indicating the role of the local community and other stakeholders in establishing the Potshini catchment monitoring network. The feed back loop indicates sharing the analysed data with the respective stakeholders.

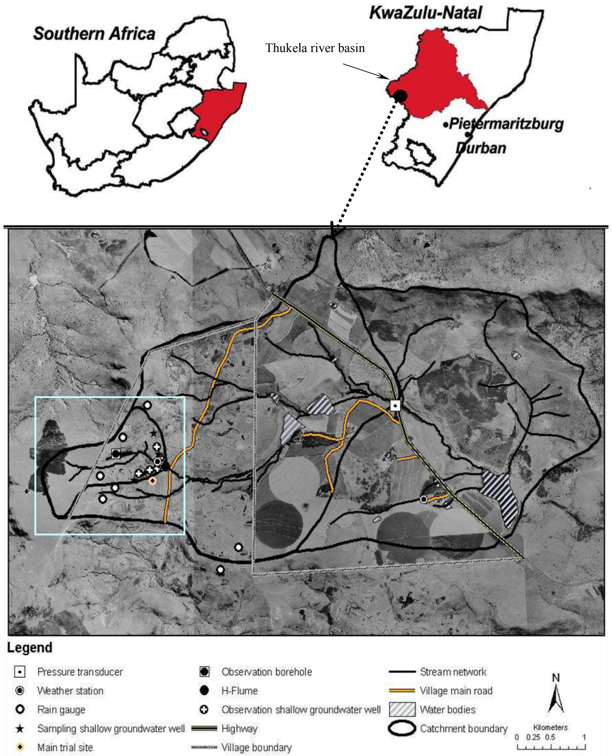

Fig. 2a. An overview of the Thukela River basin and the Potshini catchment.

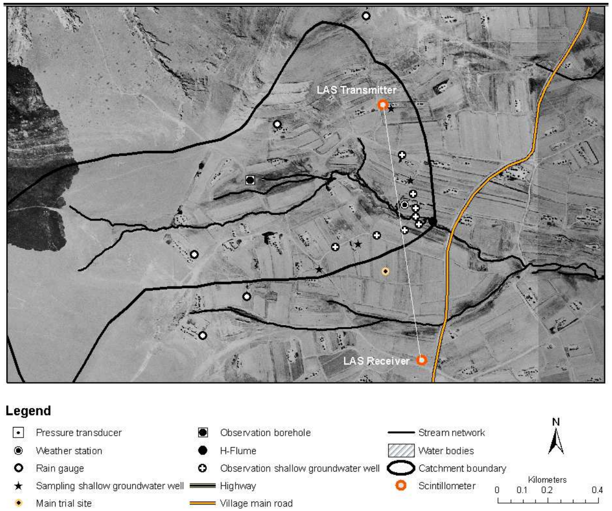

Fig. 2b. The Potshini catchment.

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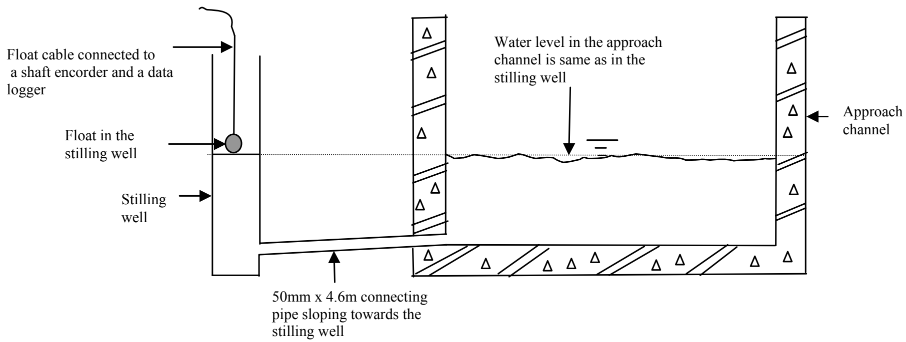

Fig. 3. A schematic diagram indicating the mechanism for monitoring the approach channel flow depth using a stilling well and float at the Potshini H-Flume. The width and length of the approach channel are 2.684 m and 15.4 m, respectively.

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Fig. 4. An operational H-Flume in the Potshini catchment.

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Fig. 5. A set of runoff plots in the controlled research site.

Fig. 6. A set of runoff plots under different treatments in a farmer managed trial.

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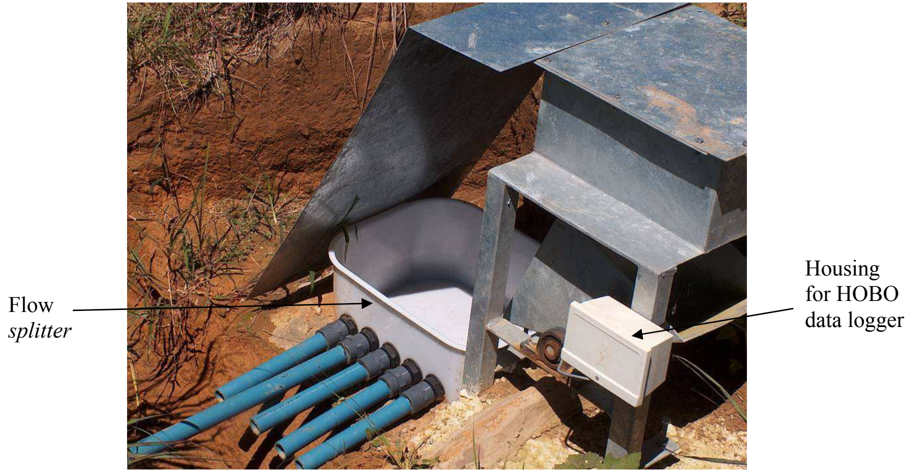

Fig. 7. A flow splitte attached to a tipping bucket, showing the five outlet pipes, only one of which drains to the sample tank.

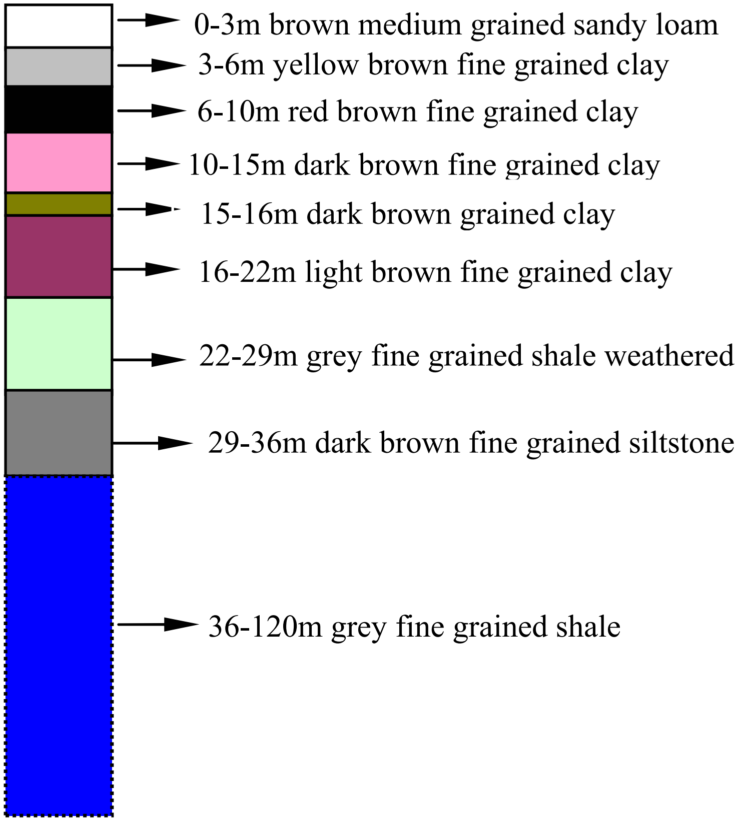

Fig. 8. Borehole log information including the lithology, grain size and colour for one of the deep observation groundwater wells in the Potshini catchment.

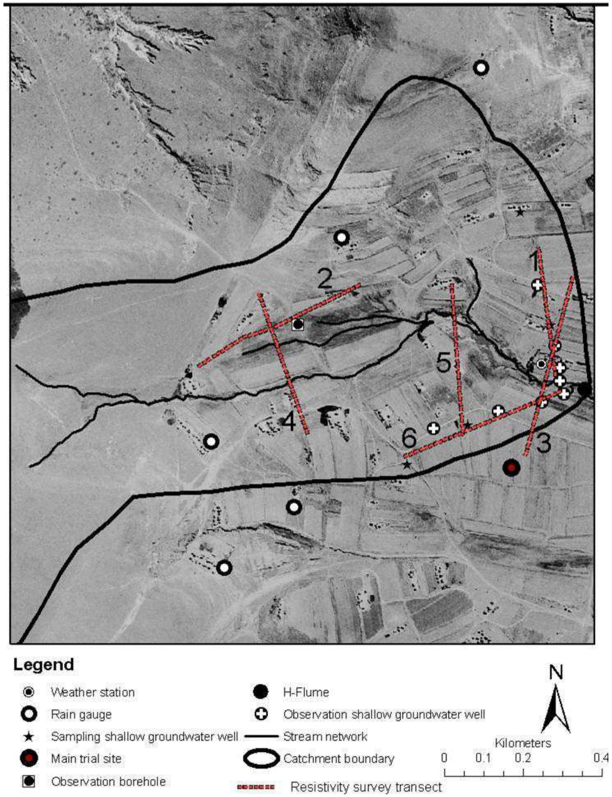

Fig. 9. Location of resistivity survey transects in the Potshini catchment.

Fig. 10. The receiver of the Large Aperture Scintillometer in one of the homesteads in the Potshini catchment.

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