HYDROLOGICAL SYSTEMS MODELLING RESEARCH PROGRAMME: HYDROLOGICAL PROCESSES

Phase I Processes Definition and Database

by

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Report to the Water Research Commission on the project:

‘*Hydrological Systems Modelling Research Programme: Processes Research* ’

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Executive Summary

Environmental modelling advances which have accompanied the development s in computer technology are a mixed blessing. Whereas, in the past, we often had a plethora of environmental data without a holistic theory, nowadays we often suffer from a growing stockpile of models, many of which have not been adequately verified. Model development has become an increasingly attractive pursuit since funding is often limited, the cost of field studies is high, time and patience limited and cooperative research is often difficult and tedious. Nevertheless, modelling and process experimentation must be an ongoing endeavour that reciprocally enhance one another with sound, comprehensive experiments and observations serving as the building blocks of models. At the same time models must serve to economise experimental designs, direct objectives and test observed phenomena. The responsibility lies in the hands of environmental researchers to adhere to the modelling process and to seek out experimentalists that can assist in building and evaluating models. Even though this warning is nothing new, the effort by modeller to heed it is still as much the exception as the rule[1]. The 'Hydrological Systems Modelling Research Programme' of the School of Bioresources Engineering and Environmental Hydrology, University of Natal has recognised this need and has incorporated a vigorous effort in Hydrological Processes Research.

Observations, monitoring and experimentation of hydrological processes is especially important where perturbations to the hydrological response occur due to changes in land use or climate. Here, models alone may often fall short in predicting the changes in hydrological response, unless they are built upon the sound understanding of the hydrological processes. This understanding is imperative when catchment management issues are to be resolved, where managers must know *a priori*, the consequences to the water resource, of such practices as community settlement of grassland areas, afforestation, invader species removal, waste disposal or extensive agricultural development, whether small community based or large schemes. Conversely, the clear understanding of hydrological processes is used to assist land users in best practice options.

[1]Corwin, D.L., Letey, J. and Corrillo, M.L. 1999. Modelling non-point source pollutants in the vadose zone: Back to basics. *In:* Corwin,

D.L., League, K. and Ellsworth, T.R. (*eds*), *Assessment of Non-Point Source Pollution in the Vadose Zone. AGU: Geophysical Monograph* 108:323-342.

During this first phase of the hydrological process research, certain key projects have been addressed. A valuable set of data has been assembled and analysed. The data and analyses have been used to interpret flow generation and storage mechanisms and computer models have been used to assess the capability of these models to simulate the mechanisms. The hydrological processes are described together with pertinent conclusions and recommendations in the following sections.

Monitored Catchments and Processes

Historic and current monitoring endeavours at catchment, hillslope and local scale are summarised and a data base, designed to allow full participation and accessibility to interested researchers or practitioners, is described. The monitored catchments include the Ntabamhlope and Cedara research catchments where some records extend back to 1964. The monitoring strategies in these catchments has been radically revised and, although still plagued by vandalism, extremely valuable data are imminent where settlement of previously grassland areas is underway.

There are currently 7 catchment scale monitored areas, many of which have multiple subcatchments and 4 areas of local, field or hillslope scale monitored experiments. Selected data sets of the Weatherley research catchment and the historic Ntabamhlope catchment have been installed in the interactive data base.

Of particular importance in these data sets is that many now contain not only the traditional rainfall and runoff data, but also data reflecting the dynamics of the subsurface water. These data sets lend themselves to the description of dominant flow mechanisms, storage and uptake.

A data base, designed to interact with the USGS Generation and Analysis of Model Simulation Scenarios (GenScn) which requires the Watershed Data Management (WDM) format, will allow for access to these valuable data by practitioners, researchers and managers. The data base is continuously populated with all available and current data from the 7 catchment areas and 4 experimental areas. In order to pre-empt the development of superior data base management tools, the primary data files are stored in ASCII format.

Hillslope Hydrological Processes

The study of hillslope hydrological processes forms the backbone of the hydrological process research programme. Mechanisms of rapid and slow responses at the hillslope scale affect the magnitude of storm flow peaks at the small (< 10 km^2) catchment scale and contribute to runoff hydrographs at the large (10 – 100 km^2) catchment scale. Mechanisms of water storage during wet periods and subsequent release from hillslopes during dry periods, affect the sustainability of small catchment practices and can have a significant control on low-flow rates at the large catchment scale. Mechanisms of lateral flow, accumulation and redistribution on the hillslope will influence the nature and location of land use practices. Conversely, changes in land use practices may affect all these hillslope flow path mechanisms and therefore the perturbations in flow generation mechanisms are also important to define.

Of particular interest in this study are the hillslope flow path mechanisms in a research catchment in the Umzimvubu basin of the northern Eastern Cape province on the eastern coastal escarpment of South Africa. This area is sensitive to anthropogenic influences, where commercial agriculture, irrigation, domestic and rural settlements and forestry compete for water use. An adequate supply of water to this region is seen as imperative in the light of the recent establishment of forest cultivation. In order to provide a sound assessment of the impacts of the afforestation, the hydrological processes in typical Molteno sedimentary formations must be clearly understood. For this reason a detailed hillslope and nested sub-catchment experiment has been initiated in a 1.5 km^2 research catchment, representative of the soils, geology, topography and climate of the region.

The research catchment, named Weatherley, was established in 1995 and has been developed into a prime research location involving many institutions. The hydrological experiment was designed for the observation of hillslope processes prior to and following afforestation The Weatherley catchment is described and selected data are presented. A number of rainfall/runoff and subsurface flow events are analysed in order to identify and define the dominant hillslope processes. Two modelling exercises, performed at different scales, are presented to substantiate the flow processes defined in the analysis of the event data. Finally, the implications of these observations on the simulation of rainfall-runoff processes in large catchments are discussed and algorithms for improved simulation by the *ACRU* hydrological model are proposed.

The dominant processes on the hillslopes, identified by the analysis of monitored data, are shown graphically in Figure 1 and a summary of each mechanism and its occurrence is presented in Table 1.

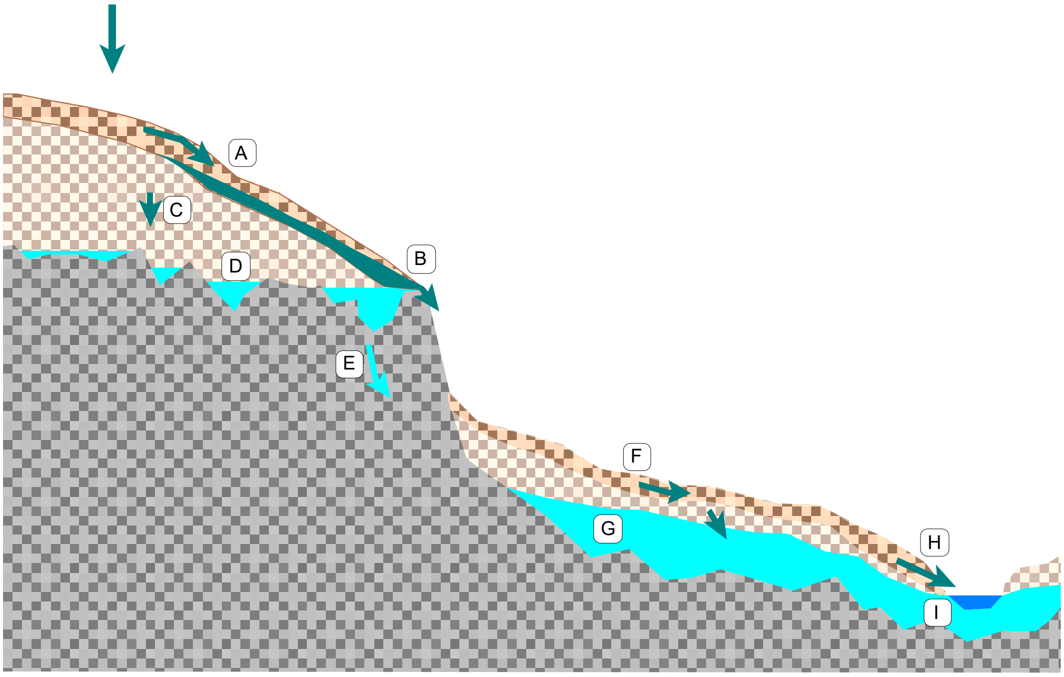

Figure 1 Conceptual model of flow mechanisms in the Weatherley research catchment.

Table 1 Summary of flow mechanisms and their occurrence.

CODE	DESCRIPTION	OCCURENCE
A	Rapid lateral flow near the surface due to macro-pore conductance. Local perched water table of short duration. Matric pressure head discontinuity with deeper perched water table, D.	In upper slope segments in downstream catchment during high intensity events and some low intensity events with large volumes (>30 mm).
B	Accumulation at the toe of the slope segment with emergence and flow over bedrock.	In upper slope segments in downstream catchment .
C	Slow percolation to water tables perched on bedrock.	In all slope segments for most events except low intensity and volume.
D	Water tables perched on bedrock and in bedrock hollows.	All slope segments. Disconnected from soil water in upper slopes of downstream catchment, but connected in lower slopes and in upstream catchment during moderate to intense events.
E	Seepage of old water through fractured bedrock.	Assumed to occur in all slope segments.
F	Rapid lateral flow in flatter marsh slopes and infiltration to marsh ground water.	Vertical recharge is more rapid than lateral movement in lower slopes of downstream catchment and in upstream catchment.
G	Marsh ground water level fluctuation	Rapid for most events in lower downstream catchment. Slower, but connected in upper catchment.
H	Exfiltration and macro-pore discharge to stream	In downstream catchment. Not observed in upstream catchment.
I	Marsh ground water discharge into stream	Assumed to occur in upstream and downstream catchments

It was found by modelling the profiles with available soil physics or hillslope models that these models clearly lack the mechanisms of flow generation in perched, near surface water tables as well as the contribution from these macropore layers into the deeper perched water tables.

Futher research is recommended in order to quantify the rates and timing of the various flow generation mechanisms by sampling natural isotopes or natural ion tracers from the various sources, It is also recommended that the simple algorithm for lateral flow generation for catchment scale models is further developed and tested. The implications of the timing of the flow generating mechanisms and the storage and release of water observed in the hillslopes also requires investigation for low flow sequences at larger scales.

Small Scale Irrigation Processes

In the framework of hydrological processes research, irrigation practices have been studied in KwaZulu-Natal where small scale community market gardens are rapidly developing and have the potential of becoming a major water user. The study includes two locations. The first, at Willowfontein near Pietermaritzburg involves irrigation by furrow and the second, at Taylors Halt, involves irrigation by hand using containers. The dynamics of the subsurface flow is monitored and modelled in detail to assess and advise upon application efficiency. The work presented in this study addresses the need for an evaluation of small scale irrigation practices, processes and efficiencies.
The study included both a social and technical system appraisal. Evaluation of soil moisture sensing equipment was used to define the soil water dynamics during rainfall and irrigation events. Computer simulation of the observed results proved successful and further scenarios of more efficient strategies could be simulated. In the instance of the Willowfontein study, it was found that the furrow irrigation events were too infrequent and were applied for too long, causing excessive drainage below the root zone. The simulation of a scenario in which the water was applied more frequently and in smaller quantities revealed a saving of drainage of 115 mm in the month simulated. In the Taylors Halt study a less frequent application was also found to save some 80 mm for the month simulated. Figure 2 shows the cumulated water draining below the root zone for the current and proposed irrigation scenarios.

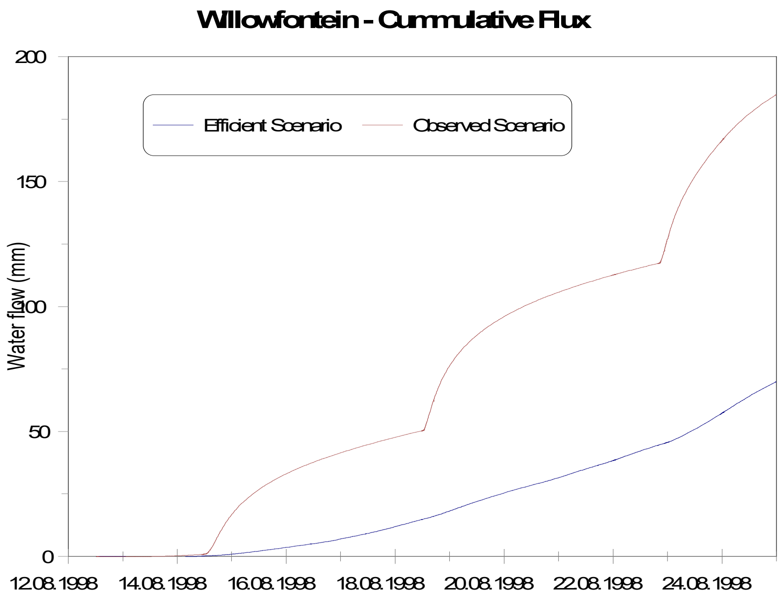

Figure 2. Comparison of observed and efficient irrigation scenarios for the Willofontein, nest 2 for August 1998.

The study highlights the use of monitoring equipment and computer simulation to assess the many nuances of small scale irrigation. The value of the study is also enhanced by the simultaneous investigation of social as well as technical aspects. It is recommended that the techniques and lessons learned in this study be communicated to the small scale farming community.

Other Hydrological Processes

The outcome of studies of contributing area sediment yield processes, irrigated mined land processes, snowmelt processes and baseflow recession curve analysis have been summarized in this project.

Contributing area sediment yield processes research is directly linked to the hillslope flow generation research and is continuing in Water Research Commission projects on hillslope hydrology and on agricultural catchments sediment yield.

Soil water processes have been studied in irrigated rehabilitated mined land. Lateral flow and accumulation of water on spoil layers has been identified and modelled. The implications for seepage through the spoil material have been assessed. This research is continuing in a collaborative study supported by the coal mining industry and the Water Research Commission.

Snowmelt routines have been included in the *ACRU* model and tested in German catchments.

Recession curve analyses have been completed in order to develop a rule based definition of base flow contributions to stream flow. It was concluded that until further analyses are forthcoming, the development of a rule based model for baseflow recession analysis in South Africa would be premature. The establishment of a readily accessible database containing streamflows and associated catchment characteristics, however, lends itself to future research in this regard.

Final Conclusion

Hydrological processes research is an on-going endeavour to improve the description of dominant water generation, uptake and storage mechanisms, particularly where land use changes influence these mechanisms. Vigorous research into hydrological processes continues at the School of Bioresources Engineering and Environmental Hydrology where catchment, riparian, wetland and local scale processes continue to be studied and the inclusion of the understanding of these processes into the larger scale simulation model, *ACRU*, is a primary focus.

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Chapter 1
Introduction

Environmental modelling advances which have accompanied the development s in computer technology are a mixed blessing. Whereas, in the past, we often had a plethora of environmental data without a holistic theory, nowadays we often suffer from a growing stockpile of models, many of which have not been adequately verified. Nevertheless, modelling and process experimentation must be an ongoing endeavour that reciprocally enhance one another with sound, comprehensive experiments and observations serving as the building blocks of models. At the same time models must serve to economise experimental designs, direct objectives and test observed phenomena (Corwin *et al.,* 1999).

Understanding the nature hydrological processes is thus essential to model development and improvement. Moreover, models which represent hydrological processes can be used to predict the consequences of land use and climate change. Hence a long-term project has been initiated to observe and measure specific hydrological processes in order to develop and refine appropriate modelling systems.

The overall aim of the Hydrological Systems Modelling Research Programme in the School of Bioresources Development and Environmental Hydrology, formally the Department of Agricultural Engineering is to

- further improve the understanding of hydrological processes
- and the modelling thereof
- using the existing *ACRU* modelling system
- in a re-structured approach

in order to

- render the modelling system user-oriented and furthermore to
- develop, revise and refine basic hydrological model input
- at point, local, regional and national scales and going beyond South Africa's borders
- using state-of-the-art techniques to provide a tool for the
- enhancement of integrated water resources related assessment, decision-making and management.

Processes research is one project component of this programme.

The specific aim of this project is to add new and to refine existing representations of hydrological processes to the *ACRU* system. Routines for many of these processes are necessary for improved modelling, are being requested by outside users for model application under conditions where a range of processes may dominate, or are processes which are anticipated will become essential to incorporate in the light of anticipated hydrological problems in southern Africa in future. The envisaged processes include

- areal precipitation representation
- improved 1-D infiltration and soil water redistribution routines
- interflow
- a 2-D hillslope/soil toposequence dominated soil water redistribution driven by DTMs
- solute fate in soils and contaminant flows
- snowmelt and freeze-thaw runoff generation
- vegetation dynamics
- soil water utilization by different land covers
- differential evaporation loadings on sloping terrain
- hydrology of wetlands
- baseflow recession
- soil loss and sediment yield.

Associated with improved understanding of hydrological processes is the continuation of research catchments and other field monitoring, with special emphasis being placed on soil water movement, solute fate in soils, sediment and wetland process studies.

During this first phase of the hydrological process research, certain key projects have been addressed. A valuable set of data has been assembled and analysed. The data and analyses have been used to interpret flow generation and storage mechanisms and computer models have been used to assess the capability of these models to simulate the mechanisms.

Research has focused on

- Infiltration, redistribution, percolation and groundwater interactions,
- 2-Dimensional migration and accumulation of water on hillslopes,
- Soil water budgeting in wetlands and vegetated riparian zones,
- Small scale community garden irrigation processes and
- Contaminant migration from localised inputs to groundwater or stream.

The first three of these aspects are included in a comprehensive study on hillslope hydrology in Molteno formations in the northern Eastern Cape Province. The fourth in a study of two community based, small scale irrigation projects near Pietermaritzburg and the fifth in a collaborative research project on the irrigation of rehabilitated mined lands. The major hydrological process projects are described in separate chapters, while a number of other process hydrology research projects which are reported more fully elsewhere, are included in a single chapter.

In Chapter 2 the all the monitoring endeavours at catchment, hillslope and local scale are summarised and the data base, designed to allow full participation and accessibility to interested researchers or practitioners, is described. The monitored catchments include the Ntabamhlope and Cedara research catchments where some records extend back to 1964. The monitoring strategies in these catchments has been radically revised and, although still plagued by vandalism, extremely valuable data are imminent where settlement of previously grassland areas is underway.

In Chapter 3 the hillslope hydrological process research is presented. This study forms the backbone of the hydrological process research programme. Extensive measurements and monitoring have been systematically phased into the research catchment, Weatherley, over a period of 5 years. The data have been analysed and dominant flow generation and storage mechanisms defined in this chapter. Implications for modelling at the larger scale with the *ACRU* model are also presented. Since the catchment is due to be afforested in 2002, the monitoring and experimentation will continue and provide an invaluable understanding of the changes in hydrological process caused by afforestation in this area.

Chapter 4 describes the study two small scale irrigation market gardens in order to assess soil water and plant uptake processes in conjunction with the social system of irrigation management in order to define the hydrological processes and assess the irrigation efficiency. Computer simulation of the observed results proved successful and further scenarios of more efficient strategies could be simulated. The study highlights the use of monitoring equipment and computer simulation to assess the many nuances of small scale irrigation. The value of the study is also enhanced by the simultaneous investigation of social as well as technical aspects.

In Chapter 5 studies of contributing area sediment yield processes, irrigated mined land processes, snowmelt processes and recession curve analysis are summarised.

Hydrological processes research is an on-going endeavour to improve the description of dominant water generation, uptake and storage mechanisms, particularly where land use changes influence these mechanisms. Vigorous research into hydrological processes continues at the School of Bioresources Engineering and Environmental Hydrology where catchment, riparian, wetland and local scale processes are being studied.

Chapter 2

Monitored Catchments and Processes

Sean Thornton-Dibb and Simon Lorentz

Monitoring of hydrological processes at the University of Natal has been an ongoing endeavour for many decades and has encompassed a wide range of processes and land uses. Historic monitoring comprised mostly the recording of rainfall, meteorological variables and runoff in small catchments with specific land uses. These data were used to verify deterministic hydrological models at a scale commensurate with the runoff measurement. Some attempts were made to define local processes, such as specific vegetation water uptake. Recently the focus has been on observing the hillslope water generating mechanisms and integrating these to simulate the observed runoff.

Two aspects of the routinely monitored catchments and local scale processes monitoring are reported here. The first details the extent of the monitoring program, both historic and current and presents a summary of the data available for all major catchments and locations. The second presents the monitored catchment database.

2.1 Catchments, Processes and Data Sets

2.1.1 Historic Catchment Monitoring (Ntabamhlope and Cedara)

Rainfall and runoff data have been collected in the Ntabamhlope-De Hoek catchments since 1964 and form an extensive data set of the process hydrology of the Natal escarpment, including wetland, agricultural and grassland land uses. The School of Bioresources Engineering and Environmental Hydrology, SBEEH, (formally Department of Agricultural Engineering) has been responsible for the maintenance of the catchment monitoring systems set since 1976, (Schmidt and Schulze, 1989a; Smithers and Schulze, 1994a). More intensive agriculture has been monitored in small catchments at the Cedara research station since 1974, (Schmidt and Schulze, 1989b; Smithers and Schulze, 1994b).

In 1998 an evaluation of the databases and an assessment of the catchment monitoring program was initiated. This evaluation is summarised in Table 2.1. Considerable useful data had been collected from the agricultural subcatchments at Cedara and these were therefore closed. At Ntabamhlope, where incessant vandalism had plagued the monitoring effort for a few years, a revised monitoring strategy was implemented. This involved reducing the number of gauged sites (Table 2.1) and increasing the level of security and the adoption of new security protocols. No sooner had all the renewed stations been established and the participation of the local community invoked, when they were all systematically destroyed by vandals. These catchments are, therefore currently not monitored. However, due to the value of the data set that may be collected in the future, when the settlement plan for the area is implemented and significant land use changes in these subcatchments come about, selected gauging sites will be reintroduced. Considerable liaison has taken place between the Chairman of the Amahlube Trust, Mr Pewa, the Department of Land Affairs (Ms Diedre Renkan) and local authorities. Successful installation of rainfall, runoff and soil water monitoring instrumentation is therefore expected prior to the 2001/2002 season.

Routine monitoring of the soil moisture status in the afforested part of the Ntabamhlope catchment has continued until September 1999, when these were removed during the felling operations.

Selected periods of the data collected through the years is accessible through the database (Section 2.2) and forms an invaluable resource for evaluating and understanding hydrological processes. These data have been used and may be used in future for assessing, among others, the following processes:

- hydrological response due to small scale agriculture in grassland catchments,
- wetland hydrology and general rainfall/runoff responses,
- hydrological responses due to afforestation of grassland catchments and
- hydrological affects of fire in eucalypt and grassland.

Table 2.1a Monitored catchment evaluation for Ntabamhlope.

CATCHMENT	LAND USE	PURPOSE	INSTRUMENT.	MET. STATION	LAND USE CHANGE	STATUS	DECISION
V7H007 (69, 87-95)	Grassland/Maize	Natural headwater Wetland processes	Weir Rain gauges	Metsite (92-99) RG 40	Amahlube T.A settlement and small scale irrigation	All down except met site	Reinstate
V7H004 (68-72, 89-99)	Forest	Grass to forest historical change	Weir Rain gauge Neutron probe	RG 23 (64-99)	None expected (Masonite property)	All down except neutron probe measurements	Reinstate
V7H005 (69, 76-82)	Feedlot/Farm	Small inlet to wetland Feedlot water quality	Weir		Farm offices will be used by Amahlube T.A.	Down	Abandon
V7H008 (69, 77-78, 93-99)	Grassland/Forest	Natural side inlet to wetland	Weir Rain gauge	RG 18 (76-95) RG 41 (88-99)	None expected	All down	Reinstate
V7H011 (63-99)	Outlet from wetland	Wetland processes Forest response	Weir Rain gauges	RG 23 (63-99) RG 14 (70-99) Metsite (92-99)	From grassland to market garden and subsistence agriculture	Weir down	Reinstate
V7H028 (70-72, 76-99)	Small grassland and natural woodlot	Natural grassland/grazing Hillslope processes	Weir Rain gauges Neutron probe	RG 14 (70-99)	From stock grazing to community grazing	Weir down	Reinstate
V7H020 (64-68,85-96)	Forest and grassland downstream of V7H028	Forest response Post fire response	Weir Neutron probe	RG 14 (70-99) RG 20 (85-95)	None	Weir down RG 20 down	Reinstate
V7H003 (70-72, 76-95)	Grassland	Small inlet to wetland on steep slope	Weir Rain gauge	RG 18 (76-95)	From grassland to market garden agriculture	All down	Reinstate

Table 2.1b Monitored catchment evaluation for Cedara

CATCHMENT	LAND USE	PURPOSE	INSTRUMENT.	MET. STATION	LAND USE CHANGE	STATUS	DECISION
U2H016	Small scale agriculture and forest	Mixed agriculture Has small dam u/s of weir	Weir Rain gauges	MC 162 MC 164 MC 165	None expected	Running	Abandon
U2H018	Forest	Forest hydrology	Weir Rain gauge	MC 181 MC 182	None expected (some felling)	Weir up Rain gauges down	Abandon
U2H020	Grassland Old forest	Steep grassland	Weir Rain gauges	MC 191 MC 202	None expected	All up	Abandon
U2H017	Agriculture						Abandoned 1997

2.1.2 Recent Catchment Monitoring (Helney Weir on Umsinduzi)

A useful period of monitoring at the Henley weir on the Umsinduzi river (U2H011) was conducted from 1994 to 1998, (Howe and Lorentz 1995; Howe 1998). These data included rainfall, runoff and flow related sediment, phosphorus and *E.coli* sampling. Unfortunately the data set is not continuous due to vandalism and instrumentation failures, however a useful set of events has been recorded. An extreme event during 1997 also inundated the recording house and the data for this event were, unfortunately, irrecoverable. Nevertheless, the remainder of the data set comprises an integrated response to forest, small scale cropping, formal and informal rural settlement land uses.

2.1.3 Current Catchment Monitoring

Catchments which are currently being monitored include the Weatherley research catchment in the North Eastern Cape Forest (NECF) development near Maclear, the Stanger catchment on rehabilitated sugar cane land, the research catchment W17 near the University of Zululand and the experimental farm catchment at Bach=s Fen, Ntshongweni. A summary description of these catchments is presented in Table 2.2. In addition, the SBEEH team collaborates in research being conducted by the CSIR at the Twin Streams research catchments, near Seven Oaks in the Natal Midlands. The research catchment at Weatherley, NECF, is described in detail in the Chapter 3 of this report and selected periods of the monitored record have been captured into the database (Section 2.2).

2.1.4 Current Local, Field and Hillslope Scale Monitoring

While all the current catchments being monitored include the observation of local and hillslope scale processes, there are a few locations where these processes are being observed without the integrated runoff measurements. The characteristics of these locations are summarised in Table 2.3 and include hillslope transects in forested (Ben Vollich), stocked grassland (Kokstad), and irrigation processes on rehabilitated mine land (Kleinkopjes) and in a market garden (Willowfontein/Taylors Halt).

Table 2.2 Catchment scale monitoring status (December 2000)

CATCHMENT	LAND USE	PURPOSE	AREA (km^2)	INSTRUMENTATION	ESTABLISHMENT	STATUS
U2H011 (Henley Weir on Umsinduzi)	Mixed grassland, forest and semi-formal and formal agriculture	Sediment yield Topographic *ACRU* verification	178	Weir ISCO sampler Rain gauges	1994 - 1998 1994 - 1998 1995 - 1998	Complete Complete Complete
STANGER	Sugar cane	Sediment yield on rehabilitated sugar cane slopes	0.5	Parshall flume Sediment splitter Rain gauge	1996 - 1996 - 1996 -	On-going On-going On-going
WEATHERLEY: NECF	Grassland Afforestation: 2002	Hillslope hydrology Forest hydrology	1.5	Rain gauge Automatic tensiometers Man./Auto. g/w observation Neutron probe Met stations Nested crump weirs ISCO sampler d/s weir Runoff plots	1995 - 1996 - 1996 - 1995 - 1996 - 1998 - 2001 - 2001 -	On-going On-going On-going On-going On-going On-going On-going On-going
ZULULAND W17	Small scale cropping and grassland	Hillslope hydrology and sediment yield	0.7	V-notch compound weir Rain gauge Automatic tensiometers	1999 - 1999 - 1999 -	On-going On-going On-going
NTSHONGWENI	Small scale agriculture, grazing and wetland	Hillslope hydrology Small scale agriculture water use	0.1	V-notch compound weirs Rain gauge	1998 - 1998 -	On-going On-going

Table 2.3 Local, field and hillslope scale monitoring status (December 2000)

CATCHMENT	LAND USE	PURPOSE	AREA	INSTRUMENTATION	ESTABLISHMENT	STATUS
BEN VOLLICH: NECF	Afforested (Pine): 1994	Forest hydrology on hillslopes	Hillslope transects	Neutron probe Automatic tensiometers	1996 - 1999 -	On-going On-going
KOKSTAD	Grassland trials	Sheep stocking rate effects on runoff and erosion	Hillslope camps	Runoff plots Rain gauge Automatic tensiometers	1999 - 1999 - 1999 -	On-going On-going On-going
WILLOWFONTEIN/ TAYLORS HALT	Market gardens	Water use efficiency in market gardens	Local scale	Rain gauge Automatic tensiometers	1998 - 1999 1998 - 1999	Complete Complete
KLEINKOPJE MINE (Tweefontein Pivot)	Rehabilitated mine land	Irrigation and runoff from rehabilitated mine land	30 ha centre pivot	Rain gauge Automatic tensiometers Heat dissipation sensors Time domain reflectometry Neutron probe	1998 - 2000 1998 - 2000 1998 - 2000 1998 - 2000 1998 - 2000	Complete Complete Complete Complete Complete

2.2 Monitored Processes Database

The observation of hydrological processes is time consuming, frustrating and costly. In addition, cooperative research which would share these burdens is often difficult. Field studies and process observations are therefore not pursued by many institutions. It becomes increasingly important, therefore, that sound observation data sets are stored safely and are widely accessible to researchers and industry.

2.2.1 Database Summary (Meta Database)

A summary of the major data sets housed by the School of Bioresources Engineering and Environmental Hydrology, University of Natal, (SBEEH), is presented for catchment observations in Table 2.4 and for local, field and hillslope scale observations in Table 2.5. These summaries include the format in which the data are currently contained as well as an indication of which data sets have been installed into the interactive database. This interactive database is continuously being updated and it is anticipated that most of the data summarised in Tables 2.4 and 2.5 will be installed during the next phase of the hydrological processes research project to be completed in June 2002.

2.2.2 The Database

Selected data from the long-term monitored catchments at Ntabamhlope and at Weatherley have been integrated into an interactive database which allows for access of these data by a wide range of researchers and interested parties. The data checking systems were modified and GIS systems were integrated into the system so that the data can be easily identified and utilised.

Rainfall and runoff data collected by the SBEEH, has in the past been error checked and then stored in an ASCII based format called “agengfmt” (Schulze and Arnold, 1980).

Table 2.4 Monitored catchment data summary

CATCHMENT	RUNOFF and SAMPLING	RAINFALL	MET	SOIL WATER	SOIL PROPERTIES	GROUNDWATER	SURVEYS
Ntabamhlope/ De Hoek	V-notch compound ***MCS*** ***DB***	Automatic ***MCS*** ***DB***	1 station ***MCS*** ***DB***	Neutron probe ***Spreadsheet, ASCII***	U2H011 Hydraulic prop. ***Spreadsheet***	Historic and selected ***Reports***	Soils ***Report*** Topo ***GIS*** Land use ***GIS, DB***
Cedara	V-notch compound ***MCS***	Automatic ***MCS***	1 station ***MCS***	Neutron probe ***Reports, ASCII***			Soils ***Reports*** Topo ***Paper print*** Land use ***Paper print***
NECF Weatherley	2 nested crump weirs ***MCS, DB*** ISCO sampler (d/s) ***MCS, Spreadsheet***	3 Automatic ***MCS*** ***DB***	2 stations ***MCS***	20 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII*** Neutron probe ***Spreadsheet, ASCII***	Hydraulic and physical ***Spreadsheet***	Auto. and manual ***Spreadsheet***	Soils ***Report, GIS*** Topo ***GIS*** Land use ***GIS***
Stanger	Parshall flume ***MCS*** Flow splitter/sump ***Spreadsheet***	Automatic ***MCS***			Selected hydraulic prop. ***Spreadsheet***		Topo ***Paper print*** Land use ***Paper print***
Ntshongweni	V-notch compound ***HOBO***	Automatic ***MCS***		(planned for 2001)	Selected hydraulic prop. ***Spreadsheet***	(planned for 2001)	Topo ***Paper print*** Land use ***Paper print***
Zululand W17	V-notch compound ***MCS*** ISCO sampler ***MCS, Spreadsheet***	Automatic ***MCS***	U. Zululand ***Spreadsheet***	7 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII***	Hydraulic and physical ***Reports, Spreadsheet***		Soils ***Report, GIS*** Topo ***GIS*** Land use ***GIS***
Henley	Compound weir ISCO Sampler ***MCS***	3 Automatic ***MCS***					Soils ***GIS ISCW*** Topo ***GIS*** Land use ***GIS***

Table 2.5 Monitored local scale data summary

LOCATION	RUNOFF and SAMPLING	RAINFALL	MET	SOIL WATER	SOIL PROPERTIES	GROUNDWATER	SURVEYS
NECF Ben Vollich		Automatic ***MCS***	1 station ***MCS***	12 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII*** Neutron probe ***Spreadsheet, ASCII***			Soils ***Report*** Topo ***Paper print*** Land use ***Paper print***
Willowfontein/ Taylors Halt		Automatic ***MCS***		6 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII***	Hydraulic and physical ***Spreadsheet, report***		Soils ***Reports*** Topo ***Spreadsheet*** Land use ***Presentations***
Kleinkopjes Mine: Tweefontein Pivot	Crump weir ***CS, Spreadsheet*** [1] Ion sampler ***CS, Spreadsheet*** [1]	Automatic ***CS*** [1]	1 station ***CS*** [1]	4 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII*** Neutron probe ***Spreadsheet, ASCII*** [1] Heat dissipation, TDR ***CS*** [1]	Hydraulic and physical ***Spreadsheet***		Soils ***Report*** Topo ***Spreadsheet*** Land use ***Spreadsheet***
Kokstad	Tipping bucket: plots ***HOBO, Spreadsheet*** Flow splitter/sump ***Spreadsheet***	Automatic ***MCS***	1 station ***MCS*** [2]	3 Auto. tensiometer nests ***HOBO, Spreadsheet, ASCII***	Surface hydraulic ***Spreadsheet***		Soils ***GIS*** Topo ***GIS*** Land use ***Paper print***

MCS Mike Cotton logger system
HOBO SBEEH logger system
CS Campbell Scientific logger system

DB Selected periods entered into Data Base (ref: Appendix A)
[1] Data collected and housed by: Plant Production and Soil Science; U. of Pretoria
[2] Data collected and housed by: ARS, Cedara, KwaZulu-Nata

The objective during this contract was to transform these data into a more universal format and hence promote their usefulness and accessibility. Flow charts illustrating the two stages of data checking on rainfall and runoff data are presented in Figures 2.1 and 2.2. The first stage (Figure 2.1) comprises checks for messages entered into the logger by field technicians, date conversion from Julian format and checks for negative time steps and unrealistic data. The second stage (Figure 2.2) converts the data from column to “agengfmt” format and yields data summaries to aid checking.

It is during this second stage that the data are stored in ASCII format to be converted to the Watershed Data Management, (WDM) format which was chosen for this purpose. The WDM format is considered a common data storage format and thus reduces the number of interfaces needed for different programs to communicate. ICIS (**I**ntegrated **C**atchment **I**nformation **S**ystem) and GenScn (**Gen**eration and Analysis of Model Simulation **Scen**arios) are two of the tools that can be used with the WDM format to visualise the data, Kittle *et al.* 1998. They incorporate the merging of spatial data and time series data as represented in Figure 2.3.

IODWM, developed for the input and output of WDM data is used to import the data from a flat ASCII file format into the binary WDM format. The data is imported into the WDM with a field called ‘IDLOCN’(Location ID) which is also created in the GIS data file, this allows for the linkage of the WDM and the shape files.

The data collected by the school can be categorised loosely as Data from Memory Modules and from Data Loggers. The Data Loggers generally log at 4 or 12 minute intervals, thus being of a fixed time step. Whereas the data obtained from Memory Models(MM) is generally breakpoint data. Breakpoint being data of no fixed time interval, points are logged according to events or changes greater that a predetermined data value. This MM data is processed and can be output in a daily format which can be sent to WDM.

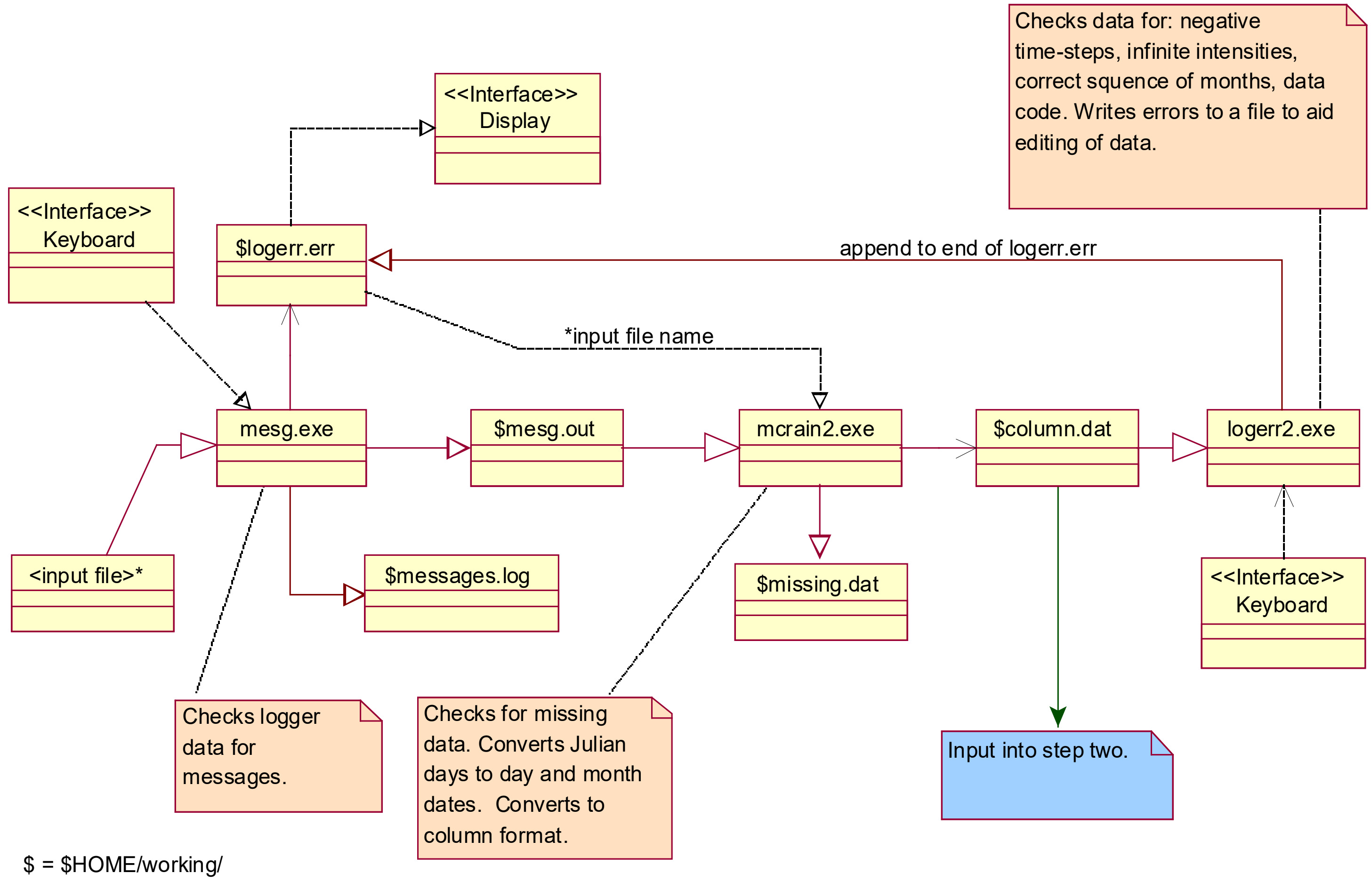


Figure 2.1 Data error checking, step 1.

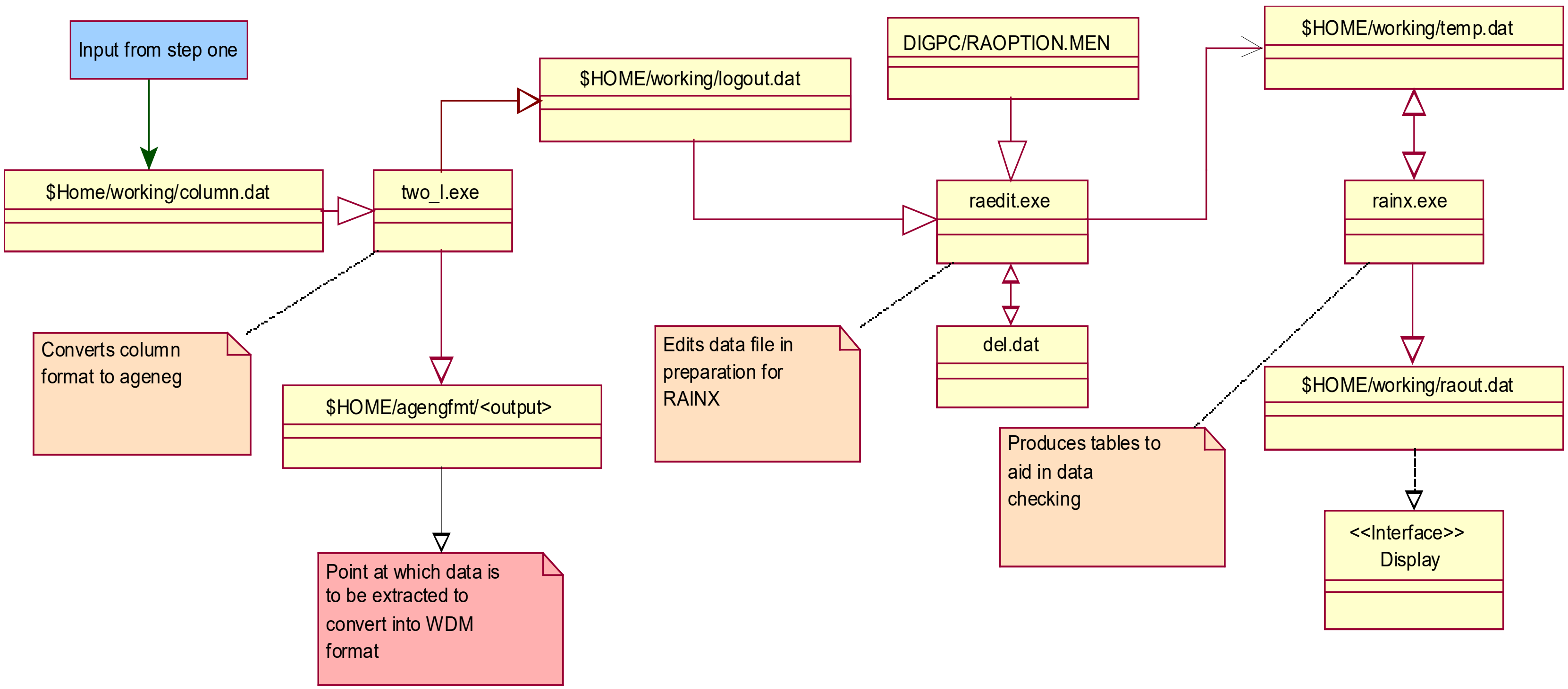


Figure 2.2 Data error checking, step 2.

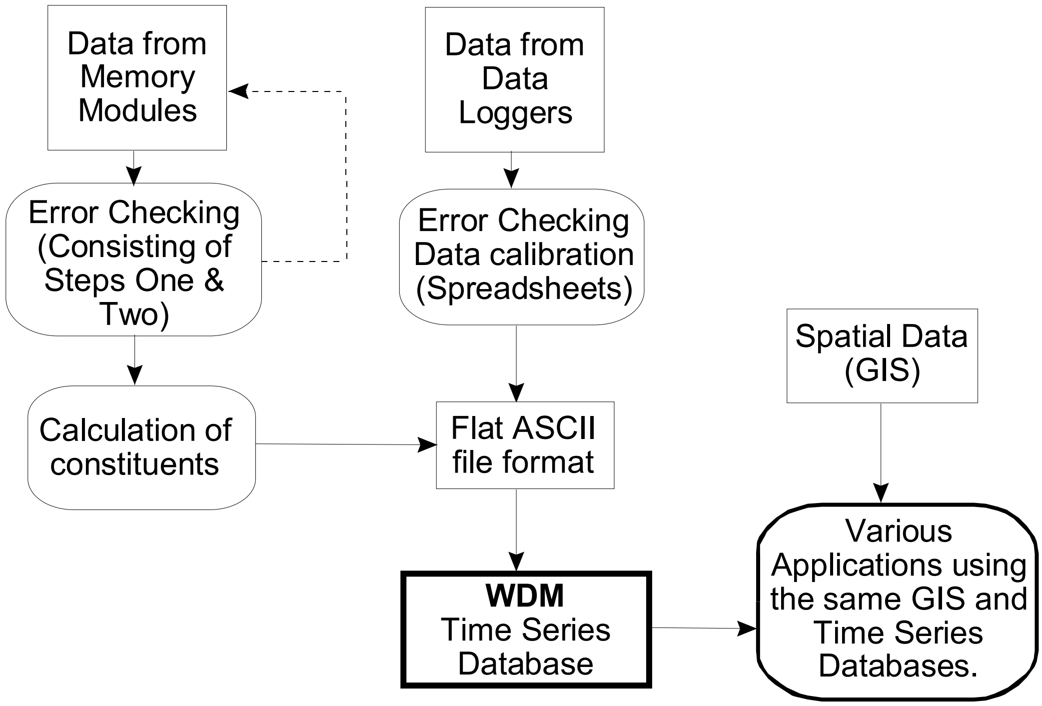


Figure 2.3. Data Flow diagram for integration of time series in WDM format and GIS.

One of the complexities of time series data is that the time axes is variable. For example, a time series originally stored at one minute resolution can also be viewed as hourly data. This is done by a process of aggregation and can be taken further to daily and monthly. The limitation obviously being the initial time resolution. This complexity results in some plotting problems when breakpoint data are stored at the original resolution in WDM since the WDM can only store data with known fixed time intervals. As a result, the WDM then stores missing values (say -99999) for all the "missing" data between the breakpoint values. These would then be included when aggregating the data, resulting in erroneous output. Recent contact with the developers of GenScn has revealed that subsequent versions will have a function allowing these intermediate values to be ignored. Thus, for the data sets of Ntabamhlope and Weatherly included in the current database, where ever breakpoint data occurred, these were first aggregated into daily values before being input into WDM. An example of the GenScn screen is presented in Figure 2.4. The installation of the GenScn program and the databases is described in Appendix A. There are still some development errors in GenScn but it is an open source program that is supported by the USGS.

As a precautionary measure data are stored in ASCII format so that they may be integrated with other database access software should these prove superior.

Generation and analysis of model simulation **Sc**e**n**arios **(GenScn)**

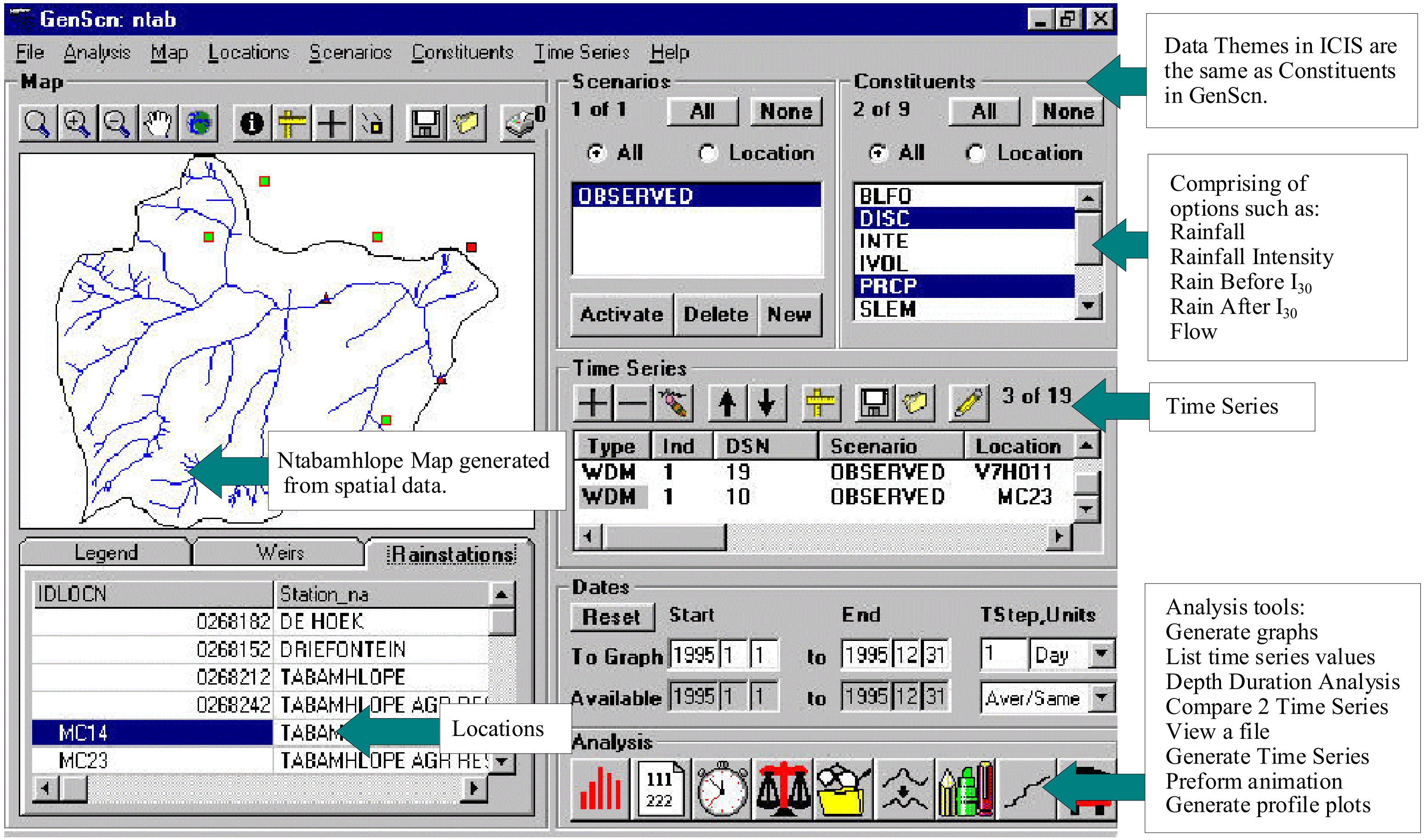


Figure 2.5 Example of GenScn application for Ntabamhlope catchment.

Chapter 3

Hillslope Hydrological Processes

Simon Lorentz and Rory Hickson

The study of hillslope flow path mechanisms is a vital component of hydrology. Mechanisms of rapid and slow responses at the hillslope scale affect the magnitude of storm flow peaks at the small (< 10 km^2) catchment scale and contribute to runoff hydrographs at the large (10 – 100 km^2) catchment scale. Mechanisms of water storage during wet periods and subsequent release from hillslopes during dry periods, affect the sustainability of small catchment practices and can have a significant control on low-flow rates at the large catchment scale. Mechanisms of lateral flow, accumulation and redistribution on the hillslope will influence the nature and location of land use practices. Conversely, changes in land use practices may affect all these hillslope flow path mechanisms and therefore the perturbations in flow generation mechanisms are also important to define.

Of particular interest in this study are the hillslope flow path mechanisms in a research catchment in the Umzimvubu basin of the northern Eastern Cape province on the eastern coastal escarpment of South Africa. This area is sensitive to anthropogenic influences, where commercial agriculture, irrigation, domestic and rural settlements and forestry compete for water use. An adequate supply of water to this region is seen as imperative in the light of the recent establishment of forest cultivation. In order to provide a sound assessment of the impacts of the afforestation, the hydrological processes in typical Molteno sedimentary formations must be clearly understood. For this reason a detailed hillslope and nested sub-catchment experiment has been initiated in a 1.5 km^2 research catchment, representative of the soils, geology, topography and climate of the region.

The research catchment, named Weatherley, was established in 1995 and has been developed into a prime research location involving many institutions. The hydrological experiment was designed for the observation of hillslope processes prior to and following afforestation. In this chapter, the Weatherley catchment is described and selected data are presented. A number of rainfall/runoff events are analysed in order to identify and define the dominant hillslope processes. Two modelling exercises, performed at different scales, are presented to substantiate the flow processes defined in the analysis of the event data. Finally, the implications of these observations on the simulation of rainfall-runoff processes in large catchments are discussed and algorithms for improved simulation by the *ACRU* hydrological model are proposed.

3.1 The Weatherley Research Catchment

The Weatherley research catchment is located approximately 5 km south west of Maclear in the northern Eastern Cape Province (31° 06' 00" S, 28° 20' 10" E) at an altitude of approximately 1 300 m above mean sea level and is 1.5 km^2 in extent.

3.1.1 Topography and land use

The Weatherley research catchment was chosen for its typical Molteno hillslope profile. The catchment drains in a northerly direction and the contributing hillslopes are divided longitudinally into two sections, separated by a Molteno sandstone outcrop (Figure 3.1). The slopes are steep, with an average of 12% on the eastern and southern slopes where the sandstone outcrop forms a bench and 18% on the western slope were the outcrop is not as well defined. Evidence of other sandstone layering is present elsewhere on the upper half of the hillslopes.

The land cover at Weatherley is predominantly Highlands Sourveld grassland (Acocks, 1975) which is generally in a moderate hydrological condition with a basal cover of 50-75% on the hillslopes, (Esprey, 1997). There are an area of previous agricultural use of some 5 ha on the western slope of the downstream half of the catchment. Marsh conditions exist along the entire reach of the stream and ranges in wide from 100 to 400 m, being widest where marshy conditions follow lines of seepage from the hillslopes.

3.1.2 Climate

Weatherley is considered to be in a marginal rainfall region for forest production with a Mean Annual Precipitation (MAP) of 740 mm and a Mean Annual A-pan Evaporation (MAE) of 1488 mm (Esprey 1997). Average daily temperatures range from 11°C in the winter to 20 °C in the summer, with severe frosts and snow falls at higher altitudes in winter. A monthly summary of rainfall, evaporation and daily temperatures is presented in Table 3.1.

3.1.3 Soils and Geology

A very complex soil system exists with large spatial variation. A detailed soil survey was carried out by the Institute for Soil, Climate and Water (ISCW) and 16 different soil forms were identified within the 1.5 km^2 catchment boundary (Roberts *et al.,* 1996) . These soils display a varying degree of wetness and colour and include red and yellow apedal mesotrophic soils as well as neocutanic and hydromorphic soils. The western slope of the catchment is dominated by brown to dark reddish brown Hutton form with sandy loam soils at the surface and sandy clay loam subsurface soil. The Clovelly form is also encounted with bleached loamy sand and sandy loam topsoils on brown sandy loam subsoils. On areas where the bedrock is found close to the surface, well-drained soils with unconsolidated material are found. The eastern slope of the catchment showed a greater variation of soil forms ranging from the dominantly Kroonstad form to Katspruit, Wesleigh, Oakleigh and Tukulus forms. Large areas of shallow lithosols with bleached sandy loam surface soils and bare rock are found. The marsh soils are mainly Kroonstad form.

A geological survey was conducted by Esprey (1997). The geology of the area is described as predominantly mudstone shale and sandstone of the Molteno Formation, as well mudstone and sandstone from the Elliot Formation. There are two prominent dolerite dykes that transect the area running north to south on the western side of the catchment and north-east to south-west on the eastern side of the catchment (Roberts *et al.,* 1996).

A ground penetrating radar (GPR) traverse was performed across the catchment along instrumentation stations 1 to 10 in the lower part of the catchment. The GPR data were supplemented with augering to bedrock to produce the cross sectional elevation shown in Figure 3.2. The dominance of the sandstone outcrop on each side of the catchment is evident.

Table 3.1 Climatic information recorded at the Weatherley experimental catchment

Month	Rainfall (mm)	A-pan Evaporation (mm)	Average Daily Temperatures (°C)		
			Maximum	Minimum	Average
January	122.5	142.6	25.2	13.9	19.6
February	119.6	128.8	25.2	14.0	19.6
March	107.5	130.2	23.7	12.1	17.9
April	42.8	102.0	24.1	10.7	17.5
May	18.2	102.3	21.2	7.2	14.2
June	10.9	90.0	17.9	3.8	10.9
July	11.2	96.1	18.6	3.8	11.2
August	18.2	117.8	18.7	5.6	11.2
September	34.5	132.0	20.9	7.7	14.3
October	61.5	139.5	20.7	9.8	15.3
November	83.3	165.0	24.4	11.6	18.1
December	109.4	142.6	24.3	13.2	18.8
TOTAL	739.6	1488.3			

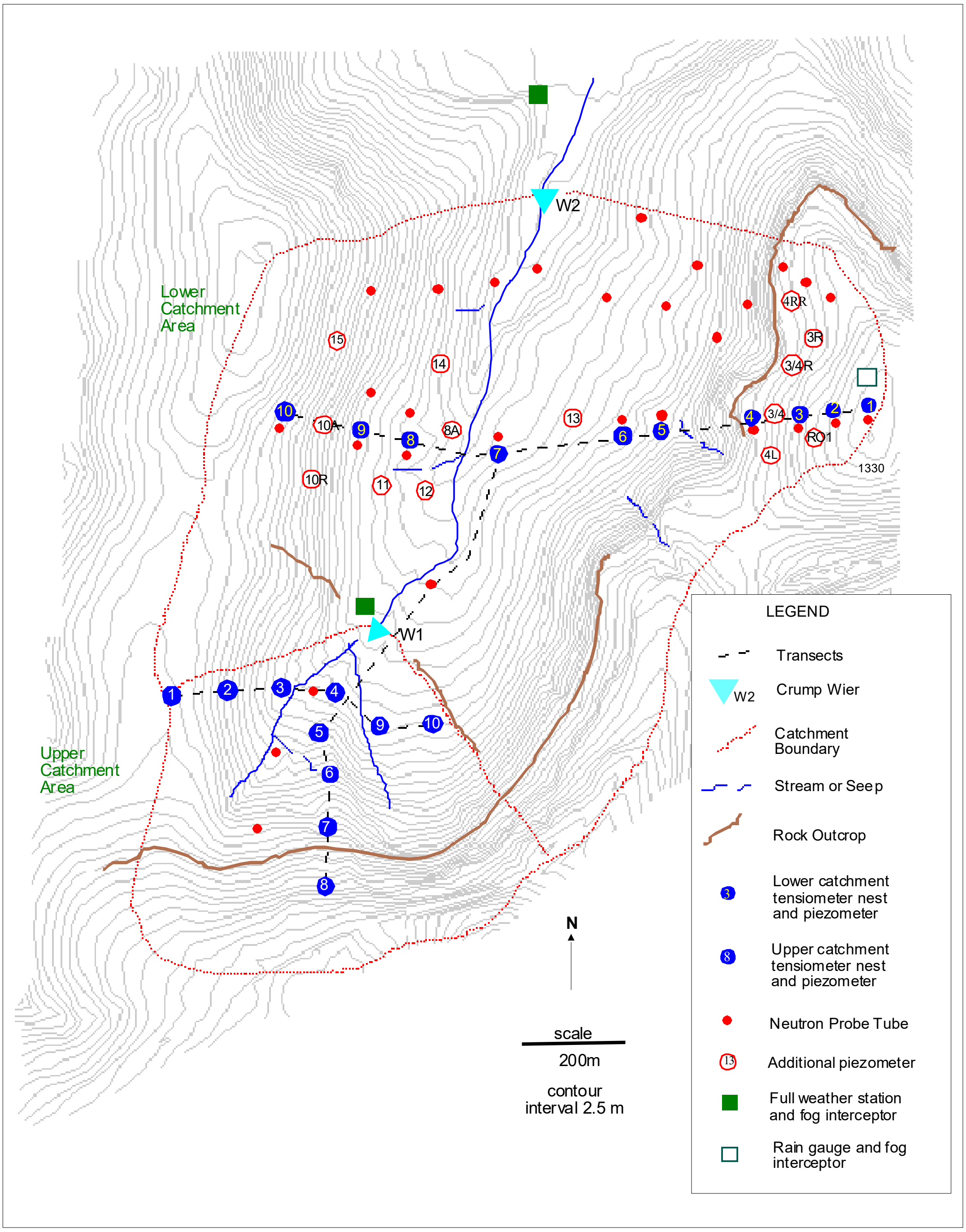


Figure 3.1 Layout of the Weatherley research catchment, showing the location of monitoring and instrumentation stations.

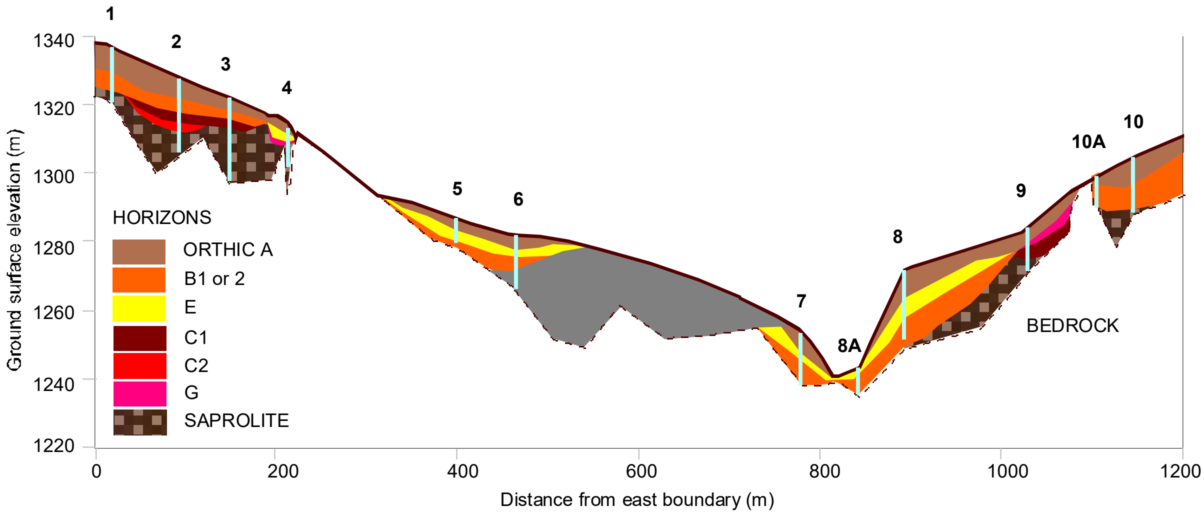


Figure 3.2 Cross section of transect 1, showing soil and bedrock profile.

3.1.4 Instrumentation

Through the 5 years of operation, the catchment has been instrumented systematically with rainfall, runoff, meteorological instrumentation and soil water sensors. The layout of the instrumentation stations, wells, access tubes and weir structures is shown in Figure 3.1 and the timing of these installations is summarised in Table 3.2.

The first automatic rain gauge was installed in late 1995 on the upper slope on the east of the catchment. This rain gauge was complemented by a fog interceptor which was read manually. Full meteorological stations were installed at the future weir sites in September 1996. These were operated be the ISCW and comprised an automated rain gauge and wind speed and direction, radiation and temperature sensors.

The soil moisture status was initially recorded weekly via neutron probe access tubes installed in August 1995. These measurements yielded volumetric water content estimates in 29 stations set out in two major transects across the catchment. Transect 1 runs from the highest point on the eastern side of the catchment, across the stream and up the western slope. Transect 2 runs from southern end of the catchment, downstream parallel with the stream, until it intersects with transect 1. Further transect were installed downstream of transect 1 and additional tubes were placed near the major transect lines in order to measure converging seepage areas on the slopes. Tensiometers, which recorded the soil water suction and ground water observation wells were installed in December 1996, beginning with the upper slope section on the east side of the catchment, these stations, or nests, were numbered 1 to 4. (Figure 3.1). Numerous improvements to the recording and automation of the tensiometers took place in the downstream part of the catchment until, in January 1998, the first major transect was instrumented with automatic tensiometers and ground water level sensors at nests 1 to 10. Instrumentation of the upper part of the catchment followed quickly in September of that year. This phased approach of the introduction of soil moisture sensing instrumentation allowed for a thorough study of the upper section of the hillslope before the entire cross section was studied. The instrumentation of the upper part of the catchment finally allowed for an assessment of flow path ways in the whole catchment. During various stages in the study, the soil hydraulic characteristics were determined from profiles excavated near the monitoring stations. In-situ ponded and tension infiltration tests were performed to determine the hydraulic conductivities, while samples from these locations were returned to the laboratory for water retention analysis. Typical hydraulic characteristics are shown in Figure 3.3, for the 0.2 m depth at station UC5 in the upper catchment, above the upper weir. A full summary of soil measurement results and the parameters of the van Genuchten and Brooks-Corey characteristic functions fitted to these data is presented in Appendix B.

The integrated runoff from the upper and lower part of the catchment could be measured after the installation of two crump weirs in December 1997. These weirs were selected since the crump weir design allows for a low water profile without excessive backwater inundating the marsh.

Table 3.2 Highlights of Weatherley research catchment development

Year	Month	Description
1995	Apr.	Team assessment of research catchment
	Aug.	Neutron probe soil moisture stations 1 – 29
	Sep.	Detailed soil survey
	Oct.	Installation of rain gauge
1996	Jun.	Soil hydraulic property measurements at nests 1 – 4 and 8 - 10
	Aug.	Ground penetrating radar transect 1 – 7
	Sep.	Installation of meteorology stations at u/s and d/s weir locations
	Dec.	Installation of tensiometers and g/w wells at nests 1 – 4
1997	Jan.	Intensive monitoring period
	Feb.	Automation of tensiometers at nests 1 – 4
	Dec.	Upstream and downstream weirs completed and instrumented
1998	Jan.	Installation of tensiometers and g/w wells at nests 5 – 10
	Sep.	Installation of tensiometers and g/w wells at nests UC1 – UC10
	Nov.	Intensive monitoring period 2
	Dec.	Automation of selected g/w wells
1999	Jul.	Soil hydraulic property measurements at nests 5 – 7 and UC1 – UC10
2000	Mar.	First afforestation assessment
2001	Feb.	Second afforestation assessment
	Jun.	Local mapping of planned afforestation
2002	Jan.	Afforestation

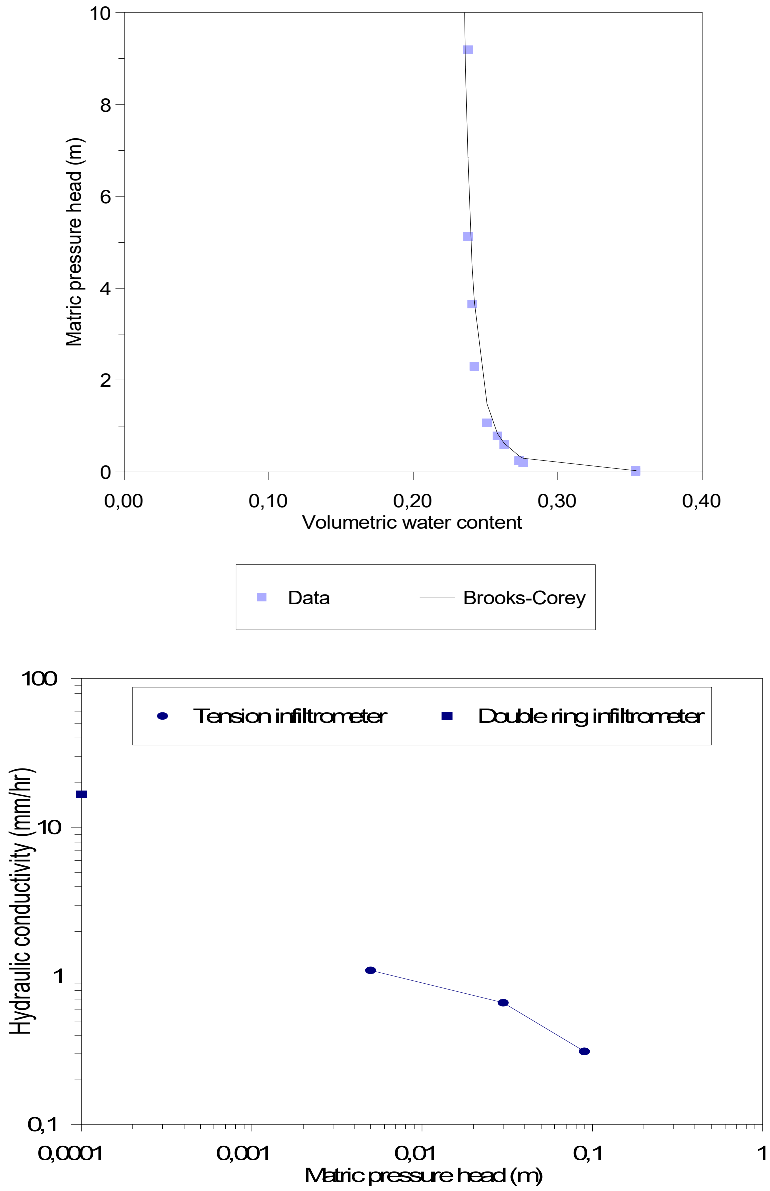


Figure 3.3 Typical water retention characteristic (above) and hydraulic conductivity characteristic (below) for the location at 0.2 m depth, nest UC5 in the upper catchment. A full set of hydraulic properties are presented in Appendix B, together with the parameters for the van Genuchten and Brooks-Corey characteristic functions. For a detailed description of the methods of analysis, refer to Lorentz *et al*. 2001.

3.2 Hillslope Data and Event Analysis

A critical study of the soil water status before, during and after rainfall events, together with the runoff and groundwater elevation observations, allow for a useful description of the mechanisms of flow on the hillslopes. These data can also be used, together with numerical models, to quantify the discharges contributed by the different mechanisms. It is first necessary to understand the interpretation of the soil water tensiometer data.

3.2.1 Interpretation of tensiometer and groundwater data

The tensiometers have been installed in groups at each of the locations shown in Figure 3.1. These groups of tensiometers, or tensiometer nests, comprise between 2 and 4 tensiometers, installed at different depths in the profile (Figure 3.4). A detailed description of the manufacture and installation of these tensiometers can be found in Lorentz *et al.* 2001. Each tensiometer's inner tubing is filled with deaired water which reaches equilibrium with the soil water through the porous ceramic cup at depth D1 below ground level. A differential pressure transducer at the top of the tensiometer tube, senses the difference between ambient air pressure, P_a, and the negative water pressure, P_w in the tensiometer tube at 12 minute intervals. The recorded difference in pressure, P_a - P_w is transferred to the depth of the ceramic by adding the pressure due to the length of the column of water, D2 in Figure 3.4.

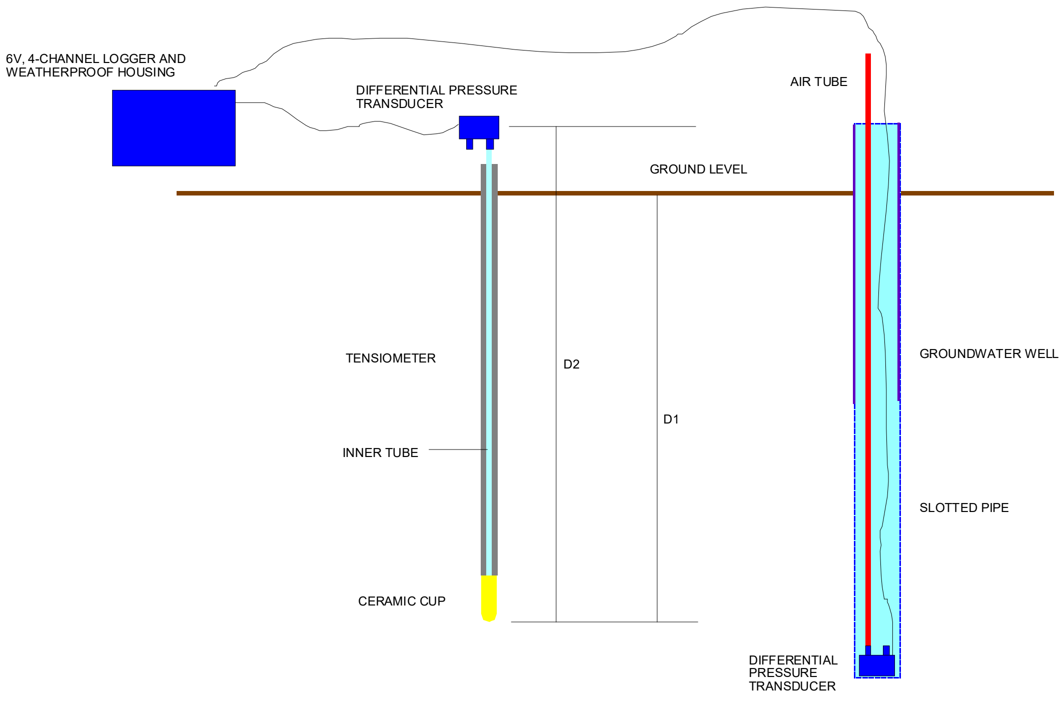


Figure 3.4 Automatic tensiometer and groundwater level recorder installation schematic.

The soil water matric pressure is defined as the difference between the non-wetting phase pressure, P_a, and the wetting phase pressure, P_w, at the level of the ceramic. For the purposes of this study the matric pressure is expressed in terms of a pressure head as $h_m = (P_a - P_w)/(\rho g)$, where ρ is the density of water and g is the gravitational constant and P_w has been corrected for the length D2 so that h_m is applicable at the level of the ceramic. With the ambient air pressure taken as reference (0), and P_w a negative pressure, (suction), in an unsaturated soil, this yields h_m positive. Although the value of the matric pressure head, h_m, is positive, it must be remembered that this reflects the degree of suction in the soil water. A high value of the matric pressure head represents a dry soil and a low value a wet soil.

A typical example of the tensiometer record for nest 2 is shown in Figure 3.5a. The matric pressure heads at the start of the record in the upper two tensiometers at 0.45 m and 0.84 m below the surface, are 0.6 m and 0.35 m respectively, indicating relatively moist conditions near the surface. The matric pressure head at 2.04 m depth is 0 m, indicating a water table at this depth. With the onset of a rain event after 2:45 pm, the matric pressure heads in the upper two tensiometers drop rapidly, indicating that the soil profile is wetting up. In fact the matric pressure heads drop below zero. Recalling the relationship for matric pressure head, $h_m = (P_a - P_w)/(\rho g)$, this negative value for matric pressure head means that the soil water pressure is positive and that a phreatic surface has moved up above the ceramic to a height equivalent to the negative value of the matric pressure head. However the interpretation of these tensiometer signals is more confounded since the matric pressure head at the depth 2.04 m does not reduce significantly and certainly does not reflect the development of the phreatic surface suggested by the upper tensiometers. This phenomenon is typical of the records from nests on the higher slopes in both the upper and lower catchments and can be interpreted by referring to Figure 3.5b.

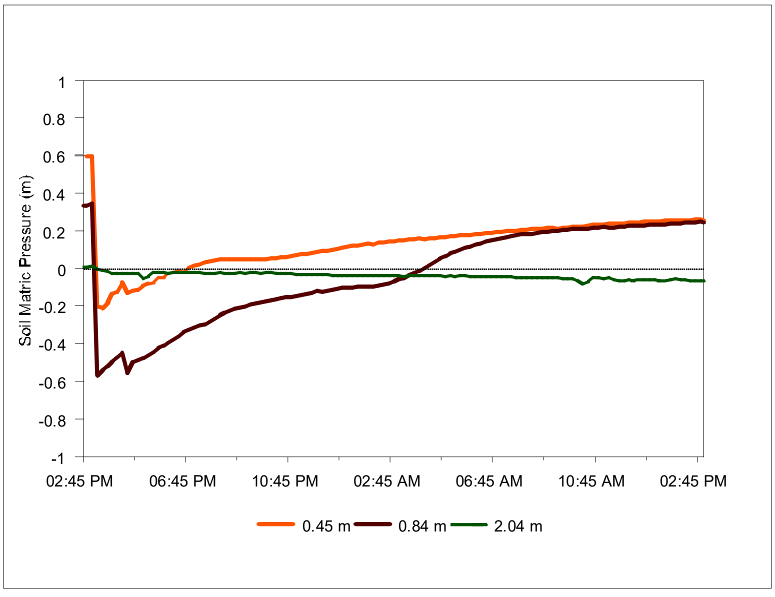


Figure 3.5a. A typical record of matric pressure head at station 2 in the lower catchment.

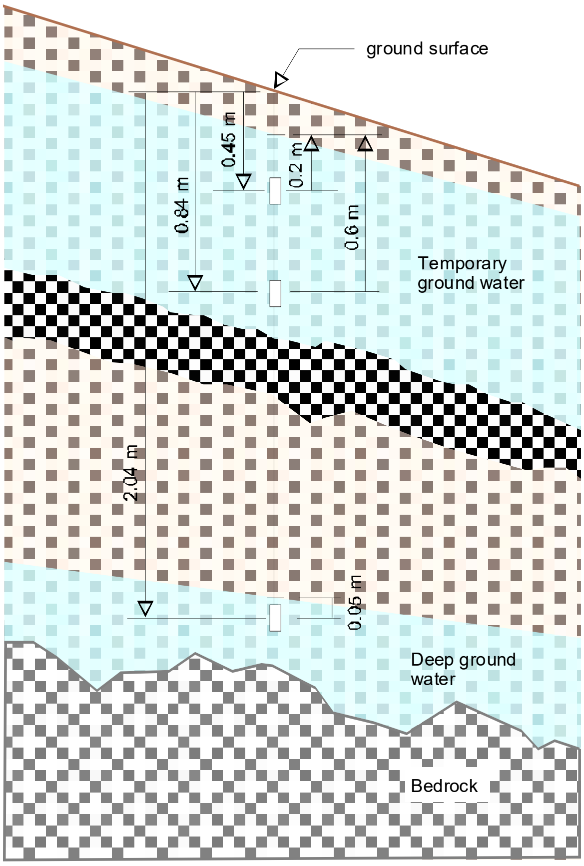


Figure 3.5b. Interpretation of tensiometer signals from the record reflected in Figure 3.5a.

The matric pressure heads of the upper two tensiometers, at 0.45 m and 0.84 m depth, drop to –0.2 m and –0.6 m respectively. This indicates a phreatic surface or water table at 0.2 m above the ceramic at 0.45 m depth and at 0.6 m above the ceramic at 0.84 m depth. These both coincide with a phreatic surface which is 0.25 m below ground level as shown in Figure 3.5b. If this phreatic surface or water table exists, then one would expect the matric pressure head at 2.04 m depth to drop to –1.8 m to reflect the same phreatic surface. However the matric pressure head at 2.04 m depth only drops some 0.05 m over the duration of the record shown. Hence, it is clear that the upper two tensiometers are recording the temporary build up of a perched water table which develops due to a layer which inhibits rapid drainage to the lower and more sustained water table, perched on the bedrock. This phenomenon could also be explained by the cessation of macro pores at approximately 1 m below the surface. Rapidly transferred water, arriving at this level via the macro pores, backs up on the slow conducting soil matrix below and forms this perched water table. The upper perched water table is quickly drained as the tensiometer signals in the upper horizons reflect unsaturated conditions again, some 12 hours after the event. However the deeper water table continues to rise as indicated be the continued gradual decrease in matric pressure head of the tensiometer at 2.04 m below ground surface. The automatic and manually recorded ground water levels in the ground water wells are also used to interpret the mechanisms of water movement on the slopes.

The study of these tensiometer records from nests located along a transect are useful in interpreting the movement of water on the whole hillslope or sections of the hillslope. Four events have been analysed in detail as examples of the flow mechanisms in the hillslopes.

3.2.2 Event 1 (Transect 1 – 4)

The first interpretation of tensiometer and ground water response comprises the upper four nests of transect 1 for rainfall events on 28 February and 1 March 1997. In this interpretation the matric pressure head values from each tensiometer in each of the nests, at three specific instants in time, are plotted on to a cross section of the transect. The distribution of the matric pressure heads throughout the hillslope section is then interpreted by interpolation for each of the three times (Lorentz and Esprey, 1998). The section of transect 1, from the hillslope crest on the catchment divide down to the first outcrop of the Molteno sandstone is represented in Figures 4.6a – c, showing lines of equal matric pressure head. On 17 February 1997, the hillslope is relatively moist, with no matric pressure heads greater than 1.5 m (Figure 3.6a). The soil is relatively driest near the surface in the middle of the hillslope section between nests 2 and 3, with a matric pressure head of 1.5 m. However the moisture content near the soil surface becomes increasingly wetter, some 40 m from the toe of the slope. The soils at the toe have matric pressure heads less than 0.2 m, indicating likely saturated conditions. With very little rain falling for the next ten days, the profile appears significantly different on 26 February 1997 (Figure 3.6b), with matric pressure heads near the surface of the mid-slope between 2 and 3 m. The deeper soil layers are also appreciably drier. However the soils near the toe of the slope are still moist, with the matric pressure head at the toe still at 0.2 m.

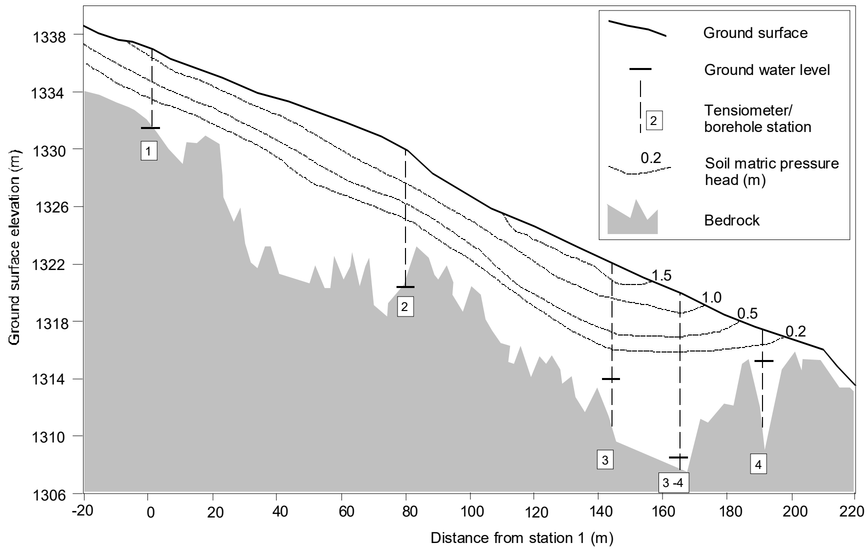


Figure 3.6a. Distribution of matric pressure head on the upper section of transect 1 (nests 1-4)

on 17 February 1997. The depth from surface to bedrock is exaggerated by 4 times.

The ground water levels do not change significantly during the 10 day period between 17 and 26 February 1997, except for a slight drop of some 0.1 m in the ground water level at nests 3 and 4. The ground water surfaces recorded in the wells are remote from the wetter surface horizons, even near the toe.

After soaking rains of 37.4 mm over 5 hours on 28 February and 36.8 mm over 5.5 hours on 1 March 1997, the transect wets up again, now with a distinct phreatic surface at the toe of the slope (Figure 3.6c) and soil water observed exiting over the outcrop.

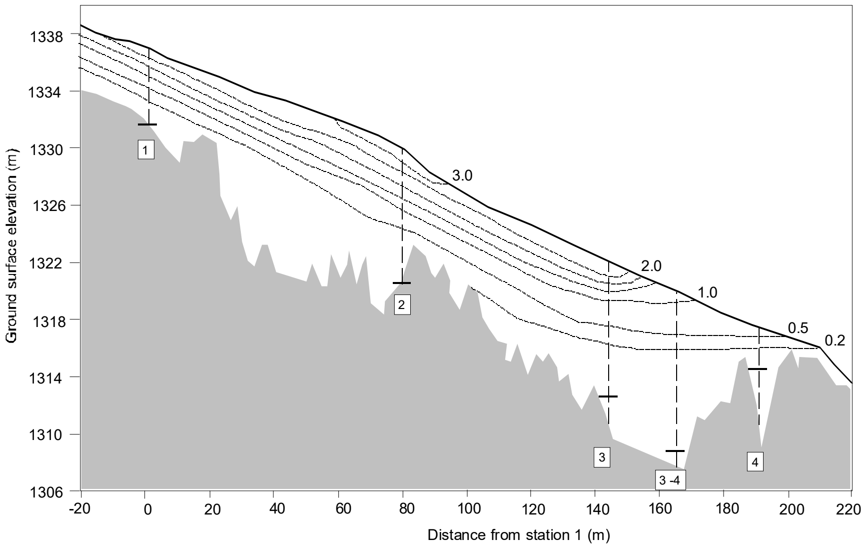


Figure 3.6b. Distribution of matric pressure head on the upper section of transect 1 (nests 1-4) on 26 February 1997. The depth from surface to bedrock is exaggerated by 4 times.

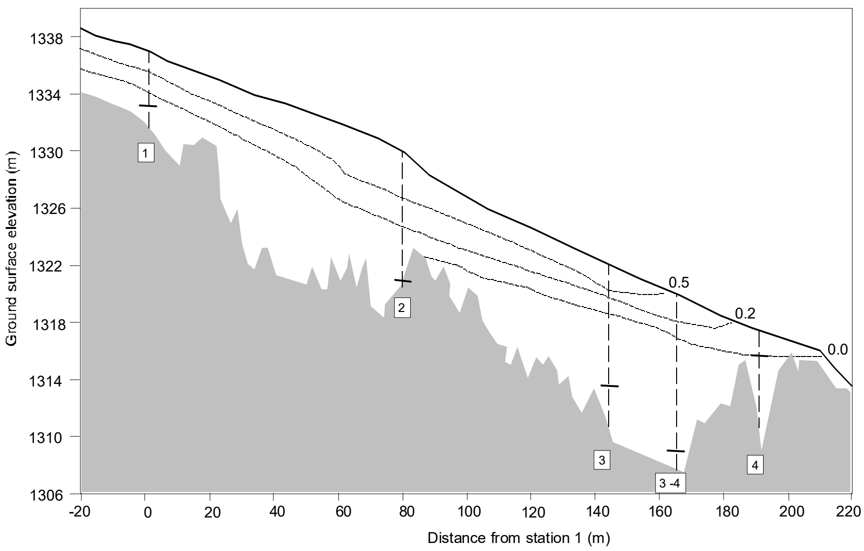


Figure 3.6c. Distribution of matric pressure head on the upper section of transect 1 (nests 1-4) on 2 March 1997. The depth from surface to bedrock is exaggerated by 4 times.

Of significance in these three scenarios is the deep ground water levels recorded at stations 2, 3 and 3-4. A perched water table, reflected by the tensiometer readings and the ground water level at nest 4, forms above these deeper ground water zones. This perched ground water, under positive pressure, contributes to the observed ground water level in the well at nest 4, and subsequently to the effluent over the outcrop, but does not appear to contribute to the water table at nests 2, 3 and 3-4, at least not within the time frame studied which was some 24 hours after cessation of the rains. As indicated in section 3.2.1, the interflow mechanisms do not seem to be influenced as much by the surface topography and ground water elevation as suggested in Thompson and Moore, 1996, as by the reverse slope of the bedrock and the hydraulic characteristics and macro pore system of the upper soil layers.

3.2.3 Event 2 and 3 (Transect 1 – 10 and runoff)

Two events with different rainfall intensities are presented in this section to illustrate dominant mechanisms that may be affected by the rate of rainfall supply. A long duration, low intensity event of 28 mm over 4 hours on 30 November, and a further 44 mm over 24 hours on 1 December, (event 2) and a short duration, high intensity event of some 40 mm over 1.5 hours on 10 December, (event 3), occurred during 1998. The response of tensiometers on transect 1 to these events, are used to identify the dominant processes in these formations together with the runoff response (Figure 3.7).

During the long duration event, (event 2), at nest 2, midway down the upper slope section defined by the Molteno sandstone outcrop (Figure 3.1), the response of the profile to a depth of 0.84 m is rapid, with significant wetting up as shown by the drop in matric pressure in the upper tensiometers (Figure 3.7, left). The matric pressure head drops rapidly below zero, indicating, again, a phreatic surface build-up in the upper layers. This condition is short lived and the profile down to 0.84 m is unsaturated again within 24 hours. However, at the depth of 2.04 m significant pressure drop only occurs after the initial rainfall of 28 mm and during the following period of low intensity rain (44mm in 24 hours) from December 1 to 2. The tensiometer at 2.04 m drops slowly from the initial 28 mm and for the next 36 hours the water table perched on the bedrock rises only 0.07 m. With the onset of the low intensity rain of 44 mm over 24 hours, the response of the water table on the bedrock is significant. The total head of water above the ceramic at 2.04 m is some 0.7 m by the time the rain ceases at mid-day on 2 December. The upper layer tensiometers at 0.45 m and 0.84 m, again respond rapidly at the start of the low intensity, 44 mm rain. Again the perched water table conditions do not last long and begin dissipating directly after the start of the low intensity period. The upper profile reaches unsaturated conditions at midnight on 2 December, prior to the completion of the rain.

During the high intensity event, (event 3), later in the month, the response in the upper layers at nest 2 is, again, rapid but the build up of the upper layer perched water table does not appear to be as high as during event 2 (Figure 3.7, right). But the response in the deeper tensiometer, near the soil/bedrock

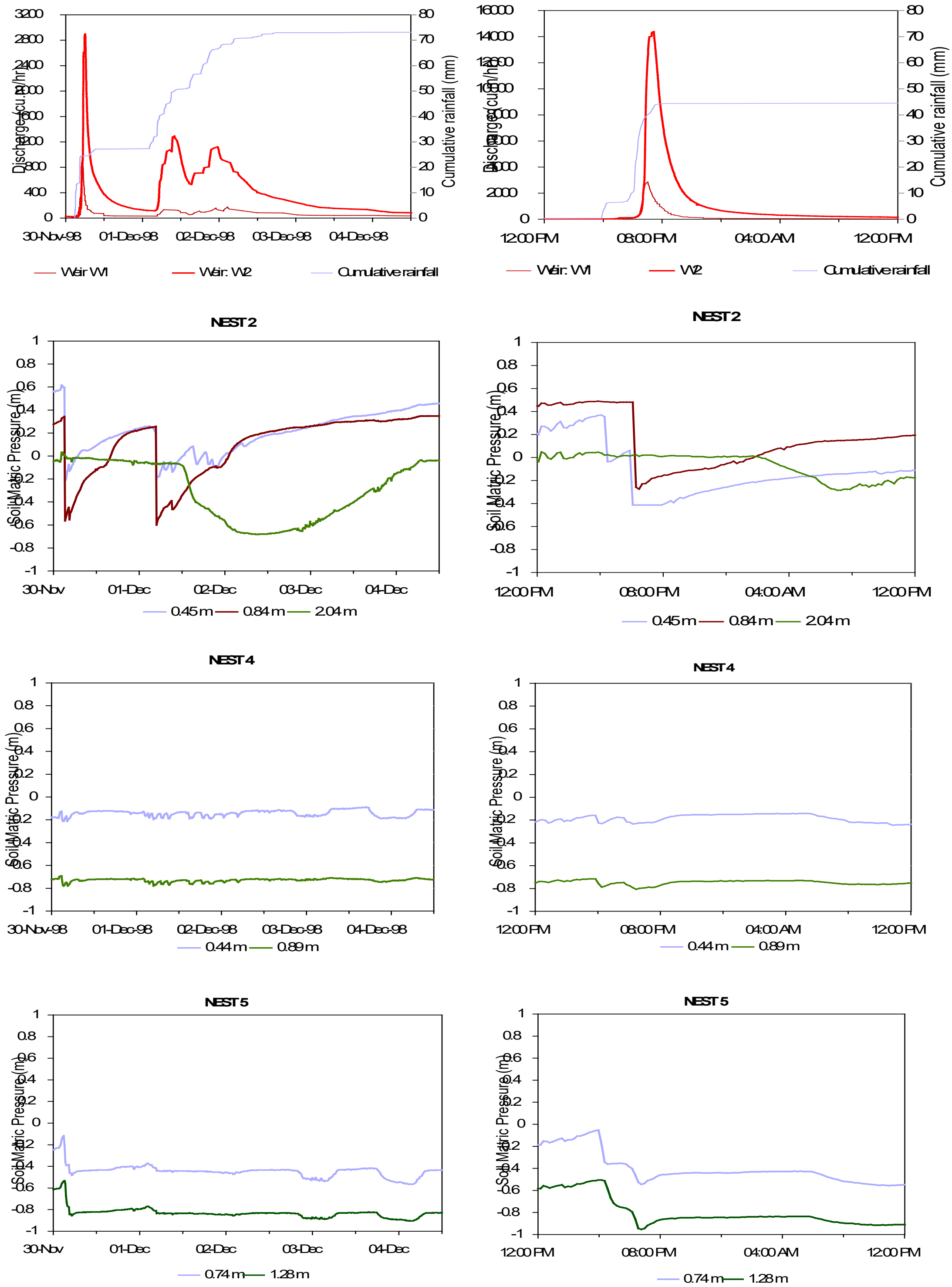


Figure 3.7 Rainfall, runoff and tensiometer time series for event 2, 30 November to 5 December 1998 (left) and event 3, 10 – 11 December 1998 (right).

contact, is negligible until some 12 hours after the rainfall, when it begins rising for about 4 hours, to a depth of only 0.3 m above the ceramic at 2.04 m, and then starts falling again. These observations suggest slow percolation to the bedrock water table from the upper layers with ponding on the bedrock occurring where the bedrock profile is irregular and subsequent lateral flow of this ponded water on the interface of the soil and bedrock. Some seepage into the fractured bedrock is possibly another cause of the dissipation of this deeper water table. However, this percolation to the bedrock appears to be greater for low intensity events which store large amount of water in the upper layers and this is then slowly percolated to the water table perched on the bedrock. The higher intensity event does not appear to regenerate the water table on the bedrock significantly. The near surface flow clearly contributes to rapid runoff, but far more so in the high intensity event than during the low intensity one. This surface runoff generation is affected by macro pore response, indicated by the rapid wetting of the profile to 0.84 m depth.

At nest 4, at the toe of the slope section and close to the sandstone outcrop, saturated conditions are prevalent prior to event 2, (Figure 3.7, left) and are maintained through the period between the two periods of rainfall. The response to event 3, (Figure 3.7 right), is a small drop in matric pressure, indicating a rise in the water table at this location. Subsurface water generated on this upper section of the slope discharges continuously over the rock outcrop while these phreatic conditions at nest 4 prevail. There is no difference in the conditions prevalent at the toe during event 2 and event 3.

At nest 5, below the Molteno outcrop, the water table rises in response to both rainfall events, although the long duration, low intensity period in event 2 does not affect the level of the water table (Figure 3.7, left). During event 2, the water table rises higher at nest 5 than it does during the low intensity event. There also appears to a response in the water table at nest 4 and 5 due to the arrival of water dissipated from the deeper horizons on the bedrock contact in the upper part of the slope. This is indicated by the rise in the water table (fall in matric pressure head) prior to 08:00 am, some 12 hours after the rainfall. Tensiometer and ground water level data indicate a steady discharge to the stream from the marsh area between nest 5 and 7 during December 1998, with small increases in water table elevation after rainfall.

The response of the opposite slope is similar to the section between nests1 and 7 although the marsh condition is not as extensive. A dolorite dyke affects subsurface mounding in the region of nest 9, while the profile at nest10 responds in a similar way to that at nest 2.

This detailed monitoring at the Weatherley experimental catchment can be used to identify dominant processes on the hillslopes. Long duration, low intensity events induce significant subsurface recharge and accumulation on the irregular soil/bedrock interface. Ponded conditions occur at the toe of the Molteno rock outcrops where emergent runoff discharges to the slope section below.
During short duration, high intensity events, the response to phreatic surface build-up on the soil/bedrock

interface in deep profiles is small. The near-surface response in soil matric pressure is rapid, similar to the low intensity event, however the runoff peak generated is five times that of the low intensity event (Figure 3.7). Surprisingly though, the runoff coefficients of the two events are similar, being about 0.41 for event 2 and 0.42 for event 3. This seems to suggest that significant quantities of water are stored in the hillslope for both low and high intensity events.

A further event, including transects in the upper catchment, is studied prior to summarising the dominant flow generating mechanisms.

3.2.4 Event 4 (Transects 1 – 10, UC1 – UC4, UC9 and UC10, UC4 – UC8 and runoff)

A series of before and after event snapshots of the matric pressure head distribution have been studied for a low intensity event between 8 and 11December 1999, where 39.2 mm of rainfall fell over a period of 80.6 hours. The rainfall and runoff from both the upstream and downstream weirs is shown in Figure 3.8. The matric pressure head distributions prior to the storm are shown at 3 pm on 8 December 1999 and after the storm at 11 pm on 11 December 1999. Three transects are represented; transect 1 in the downstream part of the catchment (1 – 7), the upper part of transect 2 (UC4 to UC8)and a third transect normal to the stream in the upper catchment (UC1 to UC4, UC9 and UC10), (Figures 3.9a-c).

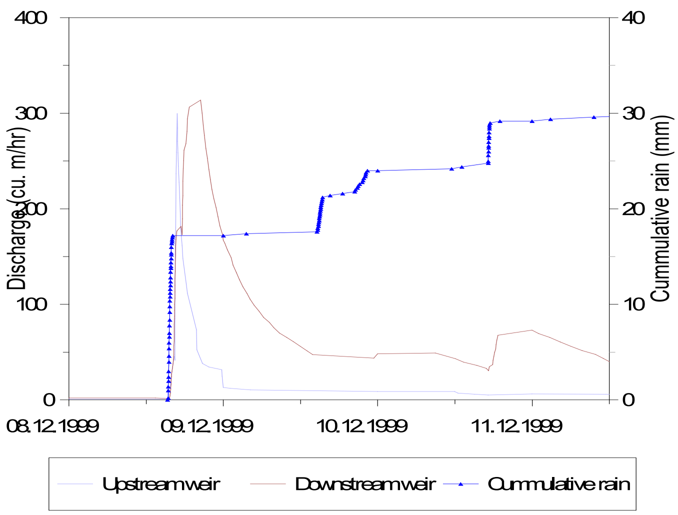
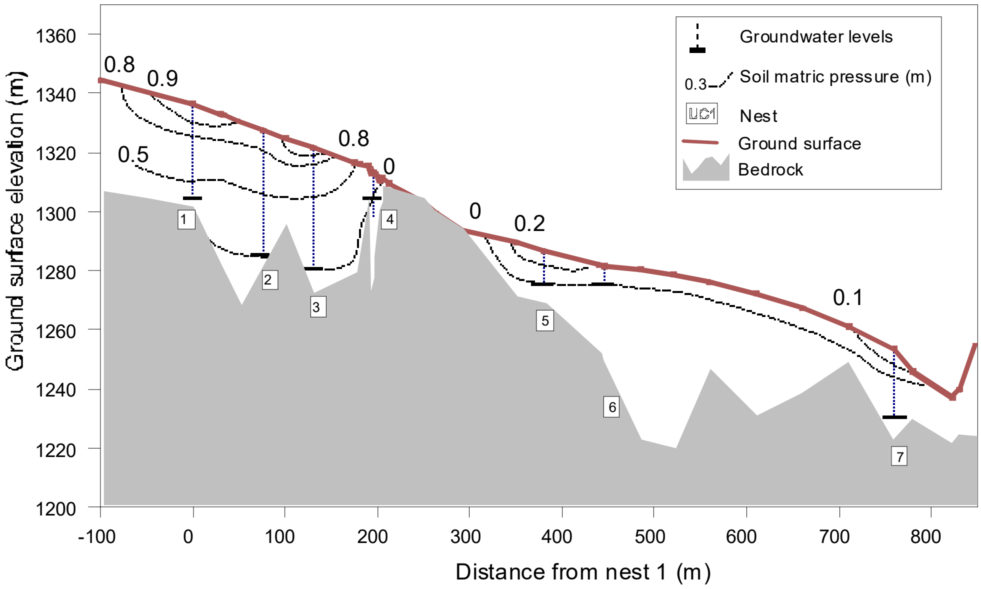


Figure 3.8. Rainfall and runoff at the upstream and downstream weirs from 8 to 11 December 1999.

The runoff peaks for both weirs is similar, but the runoff volume of the downstream weir is clearly greater than that for the upstream weir, although runoff factors are similar for the upstream catchment (0.12) and downstream catchment (0.14). Runoff responses to the rainfall begin at the same time for the upstream and downstream weirs, suggesting that the immediate runoff response is generated in the marsh areas adjacent to the streams. The matric pressure head scenarios confirm this.

In transect 1 the matric pressure heads show unsaturated conditions in the entire transect near the surface prior to the start of the rain, except at the toe of the upper section at nest 4 (Figure 3.9a). After the event the upper slope is wet in the upper 1 m of soil profile. and, in the lower slope the groundwater has risen.



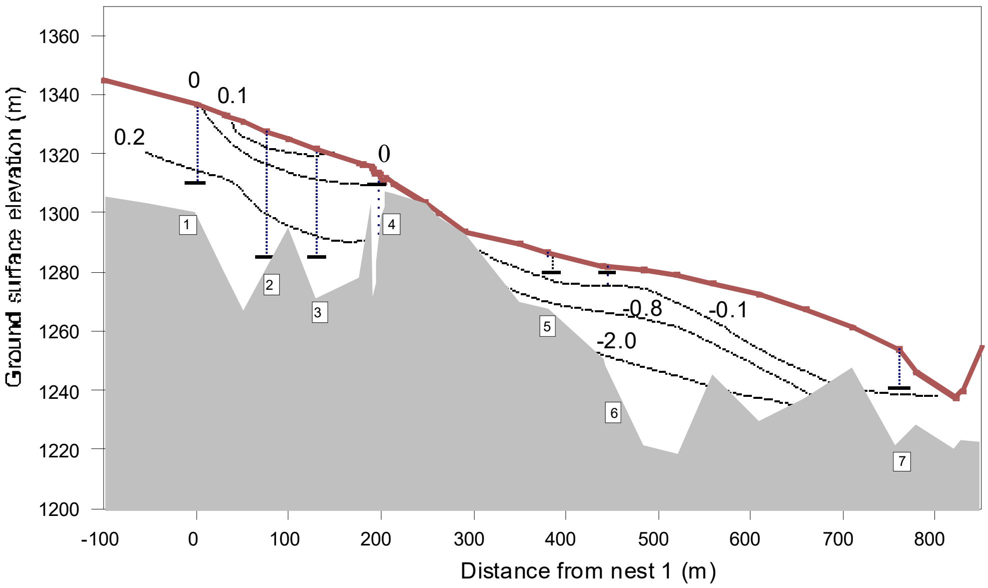


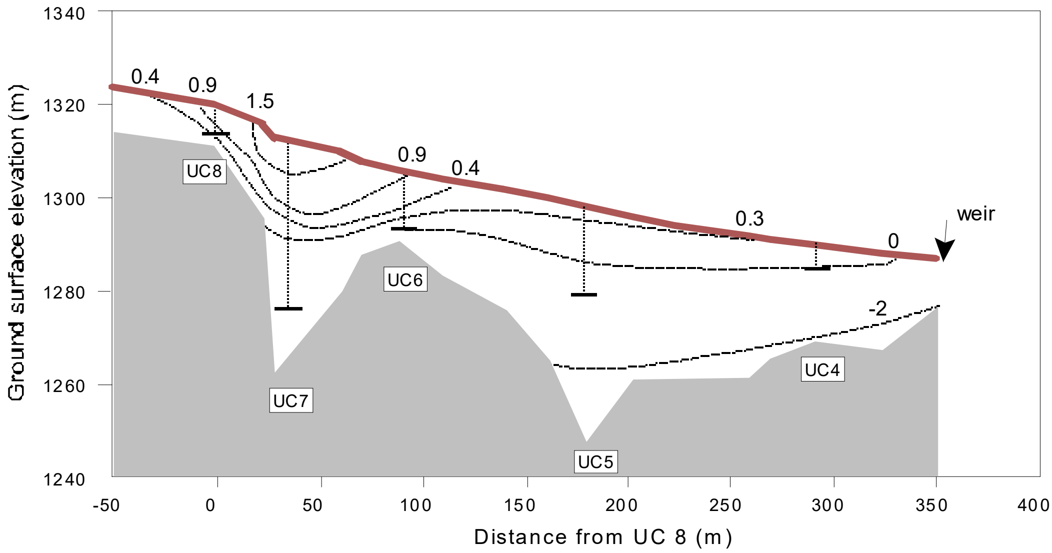
Figure 3.9a Matric pressure head distributions in transect 1, prior to event 4 on 8 December 1999 (top) and after the event on 11 December 1999 (bottom).

The ground water in this lower part of the slope were close to the surface prior to the event, but the rising water tables have increased the gradient towards the stream resulting in the immediate runoff response in the lower weir. The matric pressure distributions also reflect a rapid supply of near surface water from the upper part of the slope to the flatter lower slope, where the groundwater inundates the profile. Near the stream, at nest 7, the ground water level recorded does not reflect the matric pressure heads recorded in the tensiometers. It is evident, here ,that there may be, again, significant macro pore conductance in the near surface, contributing to the rapid response in the stream. In fact the water may exfiltrate as the slope steepens toward the stream near nest 7. In the upper part of the slope the soils remain dry below the 1 m level and there is little response in ground water levels.

In the second transect, which runs parallel to the stream in the upstream catchment, dry near-surface conditions are evident prior to the event in the higher elevations, but the slope become increasingly wetter toward the gauging weir, (Figure 3.9b). Also the soil profile, even in the upper part of the slope, becomes wetter with depth, unlike the upper part of the slope in transect 1. This is because the sandstone outcrop is not as predominant as in transect 1. After the event the entire slope is wet and the phreatic surface is close to the ground surface, everywhere downslope of nest UC7. The soil water is directly connected to the ground water, except in the deep profile at nest UC7. However, even at this location, the ground water rises rapidly after the event with contributions from the profile and upslope lateral flow on the bedrock interface.

In transect 3 in the upstream catchment, the soils are dry prior to the event and the soil profiles look similar to those of transect 1 in the downstream catchment. It is only in the vicinity of the stream that the water tables are elevated and the tensiometers reflect a connection between the soil water and the ground water at UC 3 and UC4, (Figure 3.9c). After the event, the near-surface soils wet up, although saturated conditions only extend from the stream up to the midlsope near UC2 and UC10 and are confined to the near-surface soils only. There is little response in the ground water levels and a disconnected phreatic surfaces between the upper soil profile and the water tables on the bedrock. The low intensity and volume of the rainfall, has not resulted in rapid recharge of the deeper layers on the upper slopes, but the extent of the near-stream marsh has increased somewhat upslope.

A more intense event, which occurred a month after event 4 showed significant elevation of the ground water levels in all the transects. This means that the mechanisms of hillslope water generation are affected by the quantity and intensity of events and this needs to incorporated into appropriate algorithms in order to simulate these processes accurately. In the following section a summary of the dominant mechanisms of hillslope flow generated is presented.



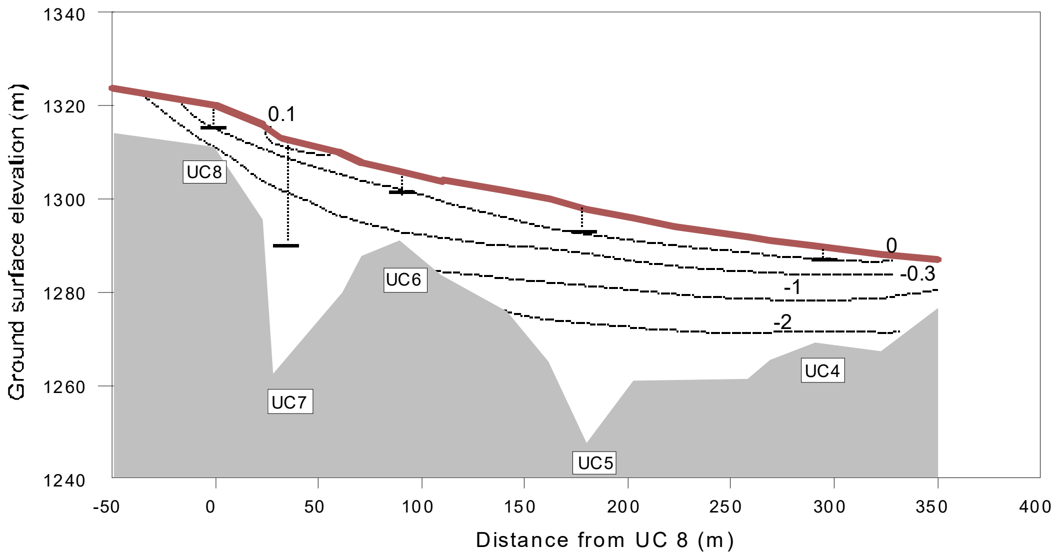


Figure 3.9b Matric pressure head distributions in transect 2, prior to event 4 on 8 December 1999 (top) and after the event on 11 December 1999 (bottom).

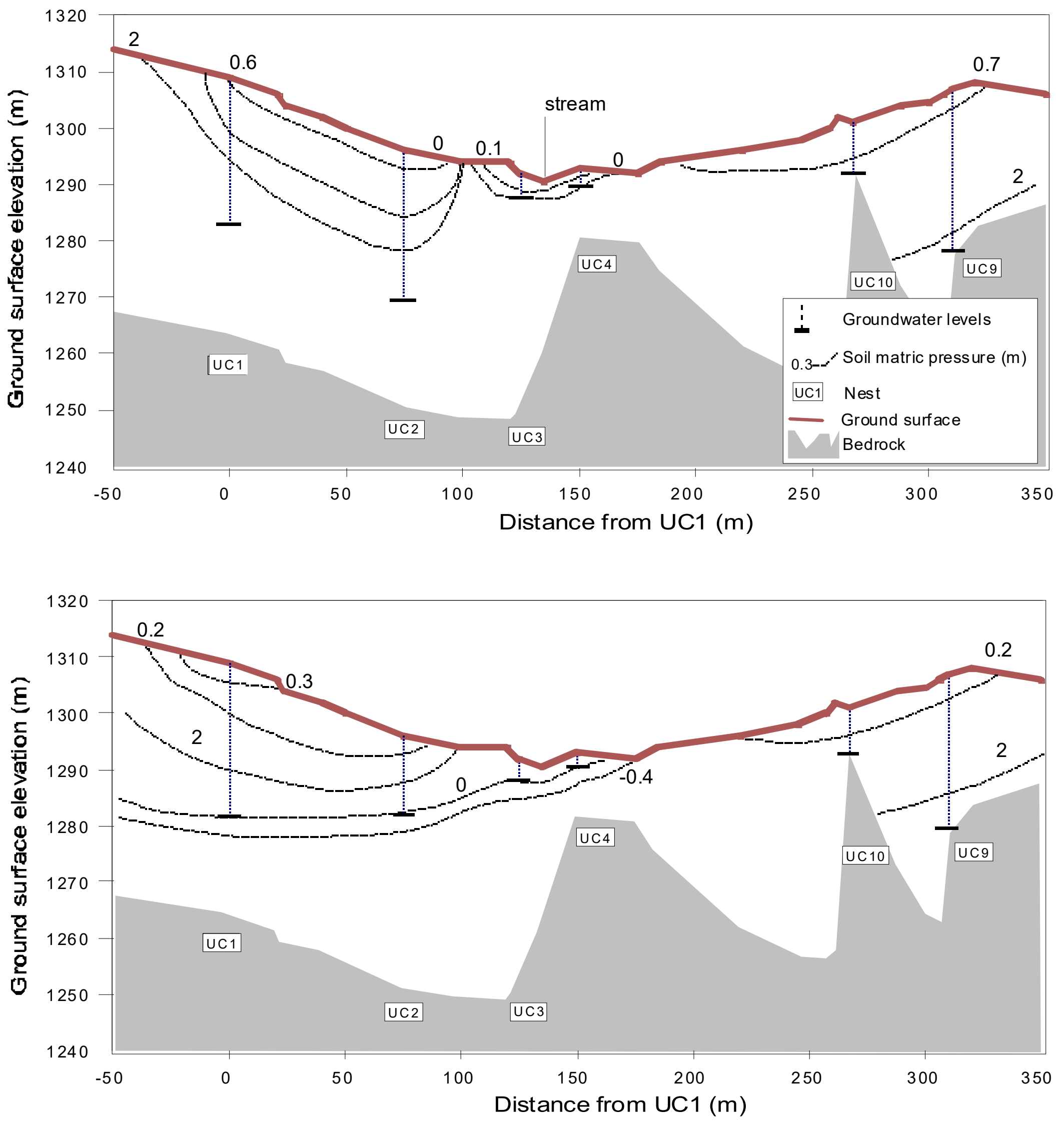


Figure 3.9c Matric pressure head distributions in transect 3, prior to event 4 on 8 December 1999 (top) and after the event on 11 December 1999 (bottom).

3.2.5 Summary of flow mechanisms

A conceptual model of flow mechanisms, based on the observations described, is presented in Figure 3.10. Brief descriptions of the mechanisms and conditions for their occurrence are listed in Table 3.3.

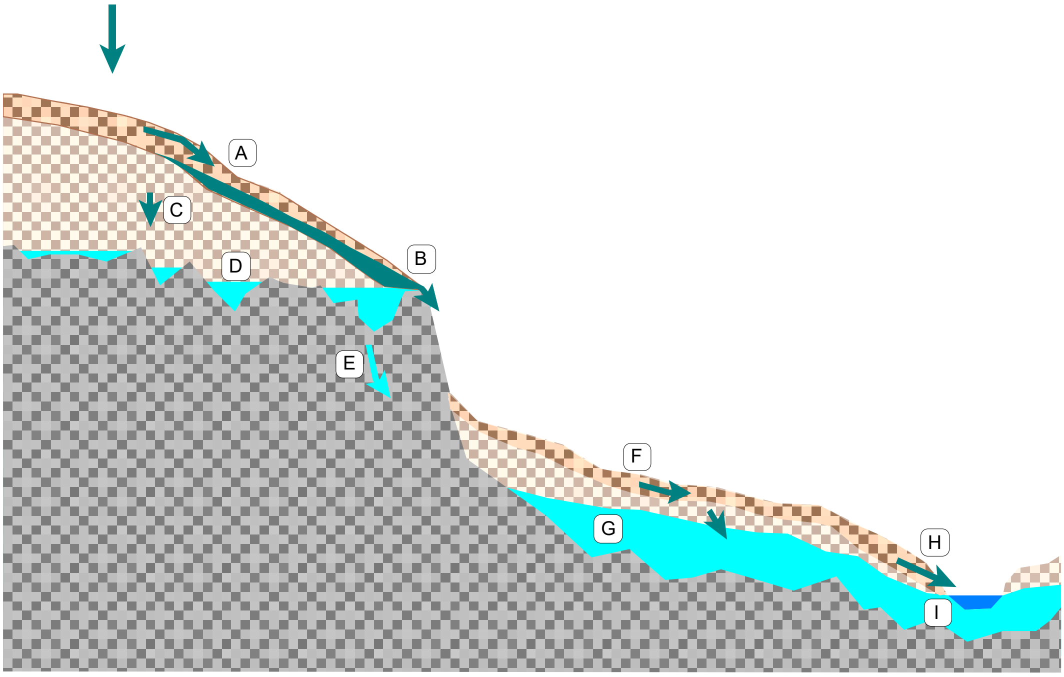


Figure 3.10 Conceptual model of flow mechanisms in the Weatherley research catchment.

Table 3.3 Summary of flow mechanisms and their occurrence.

CODE	DESCRIPTION	OCCURENCE
A	Rapid lateral flow near the surface due to macro-pore conductance. Local perched water table of short duration. Matric pressure head discontinuity with deeper perched water table, D.	In upper slope segments in downstream catchment during high intensity events and some low intensity events with large volumes (>30 mm).
B	Accumulation at the toe of the slope segment with emergence and flow over bedrock.	In upper slope segments in downstream catchment .
C	Slow percolation to water tables perched on bedrock.	In all slope segments for most events except low intensity and volume.
D	Water tables perched on bedrock and in bedrock hollows.	All slope segments. Disconnected from soil water in upper slopes of downstream catchment, but connected in lower slopes and in upstream catchment during moderate to intense events.
E	Seepage of old water through fractured bedrock.	Assumed to occur in all slope segments.
F	Rapid lateral flow in flatter marsh slopes and infiltration to marsh ground water.	Vertical recharge is more rapid than lateral movement in lower slopes of downstream catchment and in upstream catchment.
G	Marsh ground water level fluctuation	Rapid for most events in lower downstream catchment. Slower, but connected in upper catchment.
H	Exfiltration and macro-pore discharge to stream	In downstream catchment. Not observed in upstream catchment.
I	Marsh ground water discharge into stream	Assumed to occur in upstream and downstream catchments

The phenomenon of the near-surface macro-pore lateral discharges have been observed by McDonnell, 1990, but measurements in that work indicated additional rapid macro-pore or fracture flow in the vertical direction to recharge water tables perched on the bedrock. This rapid rise in deeper perched water tables or water contained in hollows in the bedrock has not been observed at Weatherley except near the stream and on the flatter march slopes. There is some percolation to the deeper perched ground water in Weatherley, but this does not appear to be sufficiently rapid to contribute to the event runoff. There are clearly advantages to pursuing the use of natural isotopes or natural chemical species in verifying the sources of the water making up the components of runoff (McDonnell *et al.,* 1991; Stewart and McDonnell, 1991; Burns *et al.,* 1998; McCartney *et al,* 1998; Brown *et al.,* 1999).

3.3 Modelling of Hillslope and Catchment Processes.

Two modelling exercises are presented briefly, to illustrate the complexity of simulating the flow phenomenon observed. The upper segment of transect 1 (nests 1 to 4) has been simulated using the HYDRUS-2D finite element soil physics model, (Simunek et al., 1994), while an event in the upper catchment has been simulated using the HILLS9 model (Hebbert and Smith, 1996; Flügel and Smith, 1999).

3.3.1 HYDRUS-2D simulation

A finite element mesh of the whole upper slope was developed using the HYDRUS-2D model. A section of the mesh for the hillslope segment near nest 2 and near nest 4 are shown in Figure 3.11. The unsaturated flow equations are solved between each node of the mesh for varying time steps, depending on the potential gradients. Three observation nodes were identified for the section at nest 2 and two observation nodes were positioned in the mesh at nest 4. These observation nodes were positioned at the level of the tensiometers so that the simulated and observed matric pressure heads could be observed.

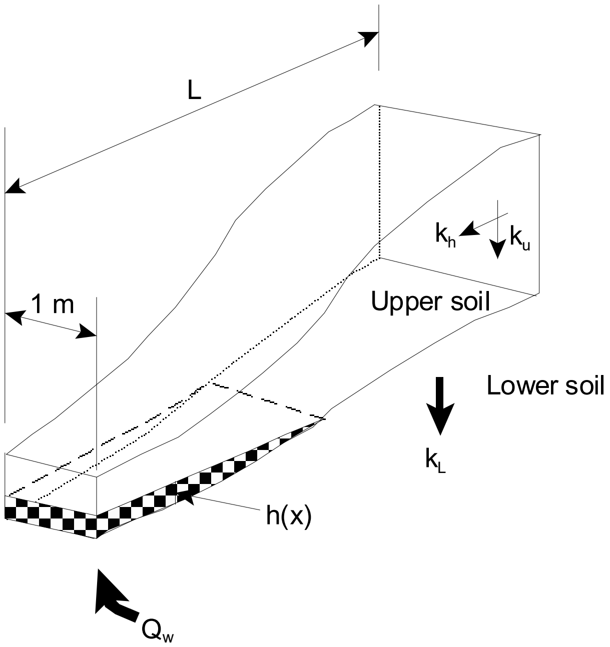
Figure 3.11a. The finite element mesh of the HYDRUS-2D model near nest 2 (above) and nest 4 (below).

The results of the simulation, shown for an instant in time after the first part of the rainfall event of 30 November 1998 in Figure 3.11b, indicate a marked wetting near the surface zone of the profile. The model simulation output 19.5 hours after the commencement of the rainfall indicates that water accumulates and flows laterally at the interface of the soil and bedrock. This is particularly evident in the model output at the toe of the slope, (Figure 3.11b). Nevertheless, the model does not simulate the degree of phreatic surface build-up near the surface that is evident in the observations. It would clearly require detailed delineation of a rapid conducting material in the upper part of the profile in order to simulate the effect of the lateral flow in the near-surface macropore system.

Figure 3.11b. Results of the HYDRUS-2D model near nest 2 (above) and nest 4 (below), 19.5 hours after commencement of the first rainfall of 30 November 1998 (event 2, Figure 3.7).

3.3.2 *HILLS9* model simulation

The upstream catchment was divided into two typical hillslope transects and the *HILLS9* model was applied to each in turn. The results of the hillslope discharges were then integrated along the stream in order to arrive at the simulated runoff. The hillslope model simulates vertical infiltration in the unsaturated soil profile using Richards equation and lateral accumulation of a saturated wedge of water perched on a semi-permeable layer using Darcy flux and mass balance principles. The model accepts a degree of convergence or divergence of flow along the hillsope section as well as a subsurface contribution to the saturated wedge from a deeper ground water source as shown in Figure 3.12.



The results of an event on 7 January 2000 are shown in Figure 3.13. The simulated hydrograph appears to respond in a similar manner to that of the observed hydrograph. The shape of the peaks, however appear to be sharper than the observed peaks indicating that the segments are responding at a faster rate than observed in the catchment. This could be the because the *HILLS9* model assumes that water in the unsaturated zone only moves in a vertical direction at the rate specified by the vertical conductivity. Saturated flow only occurs once the depth to the soil bedrock interface has become saturated and does so at the rate specified by the horizontal saturated conductivity.

Figure 3.12. Schematic representation of the *HILLS9* model concepts.

In reality, the upper catchment has numerous macropores and pipes which allow for the rapid infiltration into the deep soils. Since there is no macropore flow option in the *HILLS9* model, the simulation produces steep and sharp runoff peaks that characterise rapid runoff from a high intensity event. The absence of infiltration into the soils due to macropore flow is also evident in the fact that the receding limb of the simulated runoff does not reflect the slow release of subsurface flows into the marsh and stream as seen in the observed runoff.

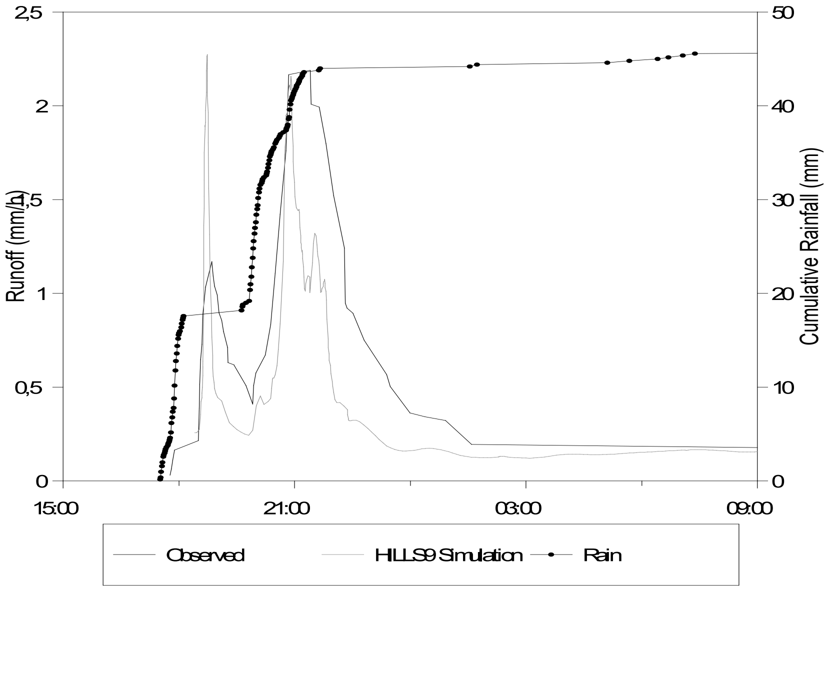


Figure 3.13. Results of the *HILLS9* simulation for an event on 7 January 2000.

3.4 Implications for Catchment Modelling

Clearly the results of this study indicate the need for a lateral flow conducting mechanism to be incorporated into simulation models for larger catchments. In addition, the inclusion of a rapid near surface flow mechanism id desirable where these macropore phenomena are evident.. An attempt has been made to include these effects into the *ACRU* model in a study of topologically influenced flow mechanisms, (Howe and Lorentz, 1995; Howe 1999). Pertinent in this study was the inclusion of a soil layer which was bounded at the base by either an impermeable bedrock, semi permeable saprolite or clay layer as shown in Figure 3.14. This boundary could just as easily be the base of the macropore continuity. The processes are simplified in this layer in that the volume of water contained in it, is assumed to be distributed in equilibrated water retention from the base to the upper boundary of the layer (Figure 3.14). Additional volumes of water into this layer move the moisture status at the bottom boundary closer to saturation. Once saturation is obtained, additional water into this layer will result in a positive head build up on the interface. It is at this stage that rapid lateral water is allowed to discharge at the rate of the horizontal hydraulic conductivity. This is obviously a simplification of the observations made in this study, but it will be pursued in the development of simple algorithms for larger scale catchment modelling.

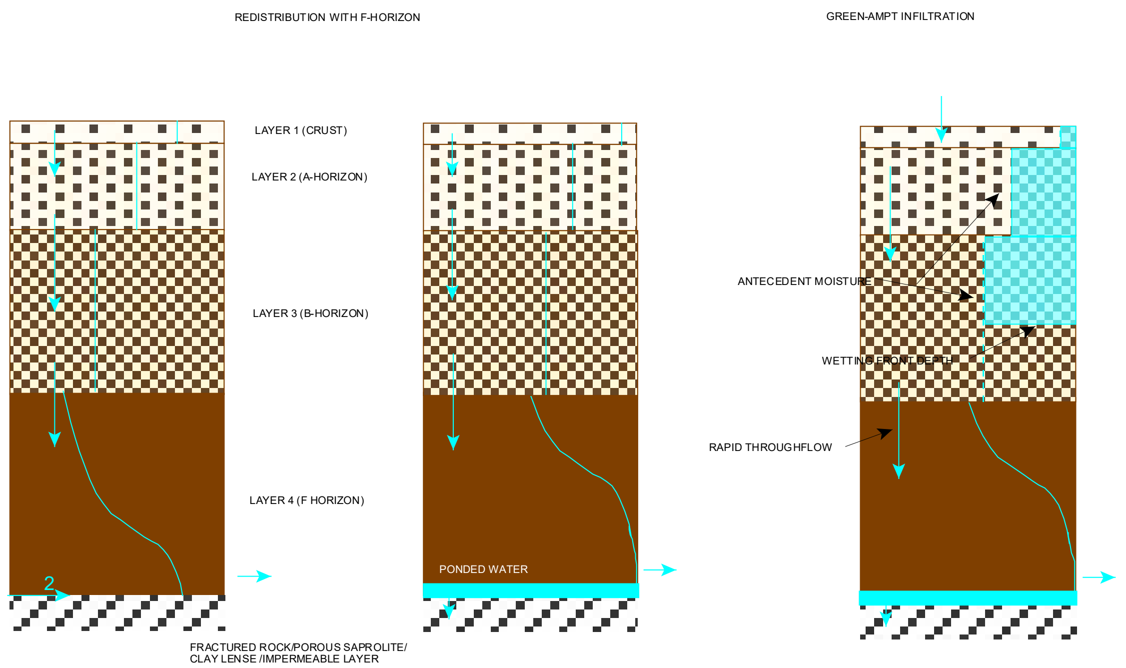


Figure 3.14. Conceptual diagram of the development of a lateral flow, perched water table by simple equilibrated pore water pressures in the lower layer.

3.5 Conclusions and Recommendations

The detailed monitoring of the Weatherley research catchment has been used to identify dominant flow mechanisms on the hillslopes. These can be summarised as follows:

- Rapid lateral flow occurs near the surface due to macro-pore conductance during intense events (40 mm in 1.5 hours or greater) or events which have large volumes (greater than 44 mm in 24 hours) for the hillslope sections which are above the Molteno sandstone outcrop.

- Local perched water tables of short duration duration (usually less than 24 hours) occur during these events. However, the matric pressure head is discontinuous with the deeper perched water table.

- In the upstream catchment, where the sandstone layer does not outcrop, the near-surface matric pressure heads are continuous with the lower water table during and immediately after most events, but not between events. The layers will then be discontinuous.

- There is a rapid increase in the ground water elevation in the flatter, lower slope sections after the commencement of rainfall. Water is supplied to this ground water body from the upper slope and from rapid vertical infiltration through the macropore system in these profiles. The matric pressure heads are continuous except where the ground surface drops steeply near the stream. Here there is tensiometric evidence of water being discharged into the stream via the perched macropore system.

- In the upper slope, the accumulation of water at the toe continuous for many days after a rainfall event and, for intense events of significant volume, there is exfiltration over the sandstone outcrop.

- The contribution of near-surface water to the deeper ground water, perched on the bedrock, during a storm event, is greater for long duration high volume rainfall than it is for short duration, high intensity rainfall.

- Modelling of the profiles clearly lacks the mechanisms of flow generation in perched, near surface water tables as well as the contribution from these macropore layers into the deeper perched water tables.

From the results of this study it is recommended that:

- While the general mechanisms of flow generation have been identified by the observations made during this study, the rates and timing of the various flow generation mechanisms require quantification. This could be accomplished by sampling natural isotopes or natural ion tracers from the various sources.

- The simple algorithm for lateral flow generation for catchment scale models needs to be developed and tested.

- Cognisance of the flow generating mechanisms need to be taken by practitioners using the hillslopes to conduct agriculture or agroforestry.

- The implications of the timing of the flow generating mechanisms and the storage and release of water in the hillslopes needs to be defined for low flow sequences at larger scales.

Chapter 4
Small Scale Irrigation Processes

Nhlanhla Sihlophe and Simon Lorentz

The challenges facing small scale irrigation development in South Africa are varied and complex. This complexity is exacerbated by the many years of systematic neglect, in tandem with material and intellectual impoverishment of the majority of participants in this agricultural sector. Attempting to juggle sustainable development of small scale agriculture, environmental and socio-economic advancement is difficult, but there is sufficient evidence in the literature to suggest that small scale irrigation is on the increase in Africa.

“Small irrigated vegetable plots, grouped into communal village gardens and supplied with water from a hand pumped well are of increasing interest to Africa, especially to women” (Collier and Field, 1998). Contributing to this increase in small scale irrigation projects in South Africa, is the high rate of unemployment. Small scale agriculture is therefore critical in playing a central role towards the reduction of poverty. This is equally true in Sub-Saharan Africa, and in response to this increase in demand for irrigation projects, the South African government has increased funds for the development of irrigated community vegetable gardens. Small scale agriculture is therefore likely to become a major water user and practices and processes require careful study.

A study conducted by de Lange (1994), identified the following as some of the problems faced by small scale farmers in South Africa:

- lack of water supply for irrigation purposes,
- lack of assured water supply,
- shortage of water supply technology,
- lack of technical support,
- lack of guidance and
- inefficient and ineffective management styles

De Lange (1994) has revealed the need to investigate crop water use so that recommendations can be made to small scale irrigation practitioners. The results of field evaluations, combined with information from farmers, suggests that less irrigation water was applied than is generally recommended for maximum crop yields (De Lange, 1994).

In the framework of hydrological processes research, irrigation practices have been studied in KwaZulu-Natal where small scale community market gardens are rapidly developing and have the potential of becoming a major water user. The study includes two locations. The first, at Willowfontein near Pietermaritzburg involves irrigation by furrow and the second, at Taylors Halt, involves irrigation by hand using containers. The dynamics of the subsurface flow is monitored and modelled in detail to assess and advise upon application efficiency.

The work presented in this study addresses the need for an evaluation of small scale irrigation practices, processes and efficiencies. The objectives of the study included a social and technical system appraisal as these two are directly linked.

(a) Social system appraisal:

- To establish the social perceptions of water use and whether, under the conditions researched, there were any existing rules of water allocation and distribution,
- To establish the organisational basis surrounding those existing rules of water allocation and distribution and
- To illuminate other social issues pertinent to small scale irrigation development.

(b) Technical system analysis:

- To test and determine whether instrumentation could be used to monitor and understand soil water dynamics under developing small scale agricultural conditions and
- To use existing modelling tools to simulate processes in small scale irrigated agriculture with a view to devising protocols for efficient irrigation practices.

An integrated approach was used to achieve these objectives. Firstly, information on existing patterns of water use and distribution as well as the organisational basis surrounding them was gathered. Simultaneous experimental work to establish crop water use efficiencies under small scale irrigation conditions was then conducted. A modelling exercise was subsequently carried out using the Hydrus_2D, soil physics model. The simulated and observed results of the irrigation processes were finally used to evaluate the irrigation efficiency and develop recommendations for efficient small scale irrigation practice.

4.1 **The research sites**

Two community gardens using different irrigation systems were identified for carrying out this work. Both these site are in Kwazulu_ Natal near Pietermaritzburg, one site is in an area called Willowfontein and the other in an area known as Taylors Halt.

4.1.2 Willowfontein

The Willowfontein research site is a community vegetable garden approximately 0.7 ha in extent. It is located in an underdeveloped area of KwaZulu-Natal at Willowfontein, about 23 km south of Pietermaritzburg city centre, at latitude 29°42' S and 30°20' E and at an altitude of 850 m. It is on a north facing hillslope with an average gradient of some 13%. The mean annual precipitation is 800 mm. The vegetation at Willowfontein surrounding the research site may be described as veld in good condition. At a distance of about 200 m from the south east corner of the fence surrounding the site is a small farm dam., (Figure 4.1). Growers maintain that the dam is a major source of irrigation water since it never runs dry, having been constructed across a perennial stream. Irrigation water flows from this dam along a channel into the upper end of the cultivated plot. It is then diverted to irrigate different sub-plots by short furrow irrigation according to the irrigation requirements of the growers. Excess water is led off to a separate perennial stream on the west of the plot. There are about 30 000 people residing in Willowfontein where it is estimated that some 60% of the people are unemployed and under such circumstances vegetable gardens are rated highly by the community since they are an important source of food as well as means of augmenting family income.

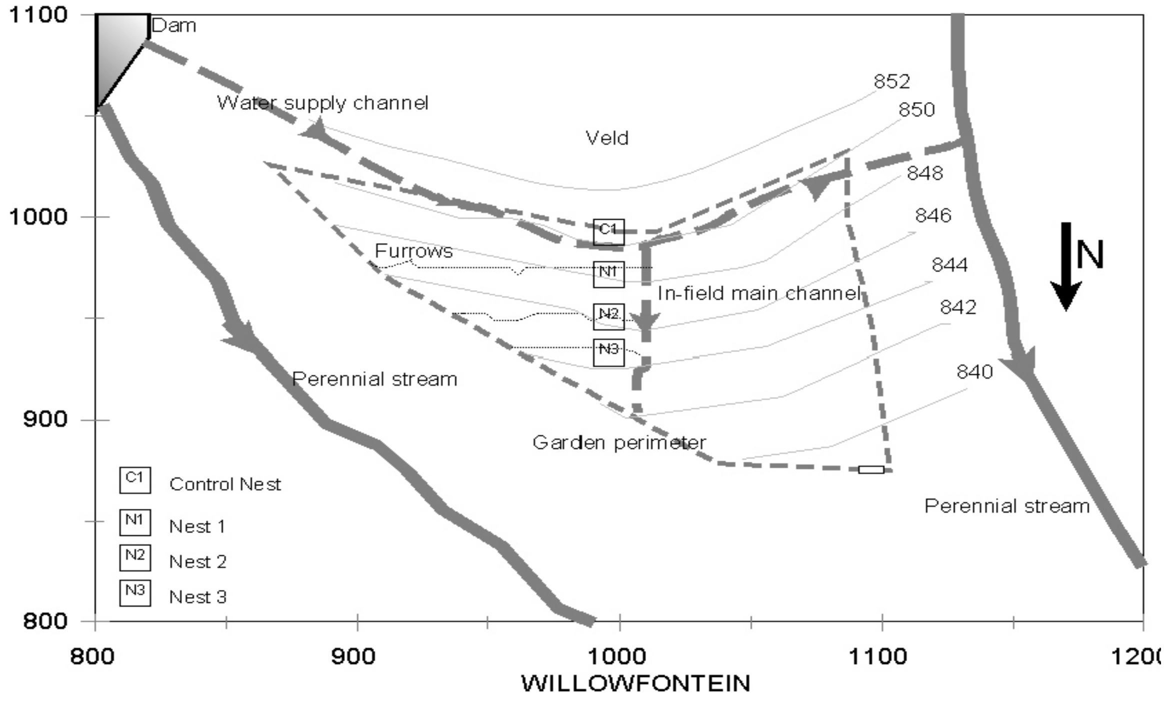


Figure 4.1 Schematic layout of the Willowfontein irrigation site.

4.1.3 Taylors Halt

The Taylors Halt research site is a community vegetable garden approximately 0.5 ha in extent. The village in which it is located is called Kwadulela, referred to as Taylors Halt in this study), and forms part of a developing South Africa. It is situated at latitude 29°36' S and longitude 30°11' E. It is on a north facing hillslope with an average gradient of 11%. The mean annual precipitation of the area is 875 mm and the altitude is 1273 m. The vegetation at Taylors Halt surrounding the site can be described as veld in good condition. At the lower part of the garden is a non-perennial stream which is the source of irrigation water, (Figure 4.2). This poses serious irrigation problems in winter when it runs dry.

It is for this reason that very little gardening activity takes place in the dry winter months. Taylors Halt is about 45 km south west of Pietermaritzburg city centre and distinctly rural in nature. The residents and growers are heavily reliant on the produce from the community gardens for vegetables. The commitment they display and the amount of time and effort they put into their gardening activities is clear evidence of this fact. The irrigation system used at this site involves collection of water from the nearby stream using containers (buckets) and during irrigation, smaller containers are then used to apply water to the crops. The volume of water applied to each crop per irrigation event is based entirely on the discretion of the irrigator and is thus reliant entirely on knowledge gained from past experience.

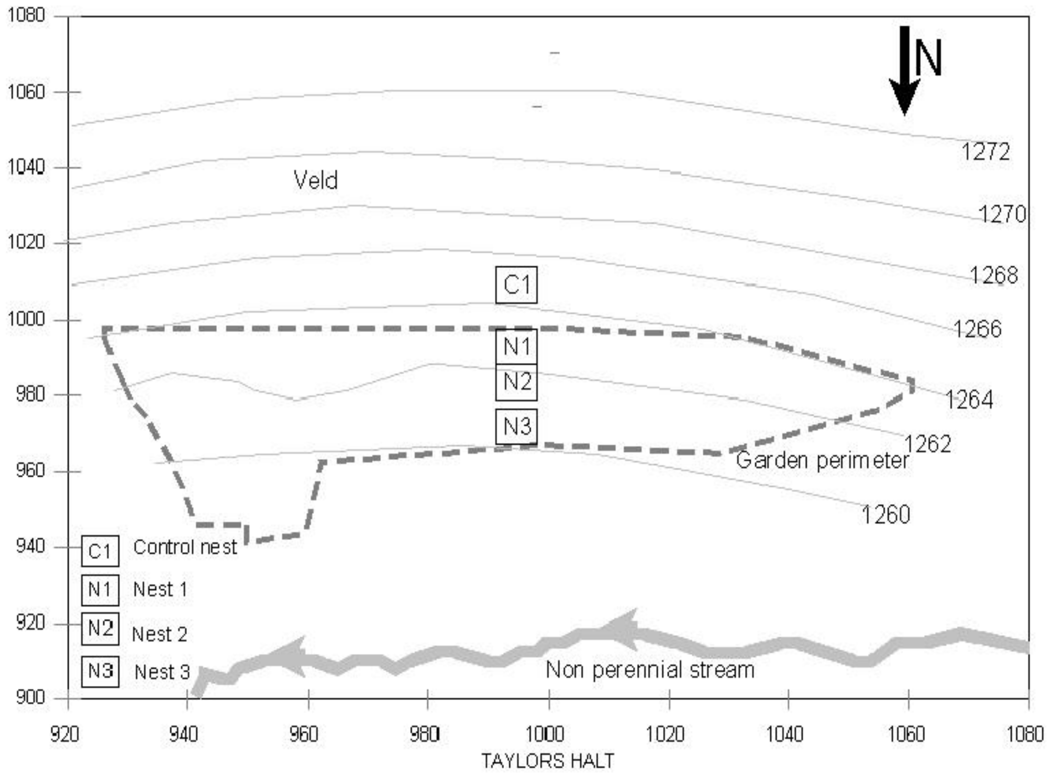


Figure 4.2 Schematic layout of the Taylors Halt site.

4.2 Methodology

4.2.1 The Social System

One of the aims of this project was to establish the social and behavioural issues that influence the patterns of water allocation and distribution in small scale agricultural conditions. This information is essential since system design and technical appraisal should be guided by the understanding and appreciation of the existing patterns of water allocation and distribution and the organizational basis that surround them (Abeyratne, 1990). Consultation became necessary at the very outset so as to inform all the stakeholders about the intentions of the research, and to solicit their input into this type of work. Consultation included organisations and agencies like the Greater Edendale Environmental Network (GREEN) and the Institute for Natural Resources (INR). This was essential in order to tap on experience and knowledge of organisations and agencies that enjoyed credibility within these communities. Consultation also included communication with tribal authorities, the department of agriculture and the community gardening groups. Meetings were arranged with the community gardening groups and in each meeting the details of the research to be carried out were explained, including foreseeable activities that would jeopardise the success of the project. Community members were then prompted to suggest mechanisms of ensuring that the project intentions were realised without any negative interference.

In both the sites, the method employed in collecting data on organisational and behavioural issues surrounding water use and allocation, involved observations and informal discussions with individual growers conducted during the process of carrying out on site experiments. Structured interviews with leaders from each of the groups were also held. This approach also helped a great deal towards assembling what is known as the indigenous technical knowledge, i.e. the community's understanding of the physical system around them. In this case, special reference was made to the community's agricultural activities. Data collected were analysed and the results are discussed in subsequent sections.

4.2.2 The Technical System

4.2.2.1 Climate

Climatic information, typical of both sites, is given in Table 4.1. These data were obtained from the climatic station, 0239756W situated at latitude 29°36' S and longitude 29°36' E. This station is at a distance of about 20 km from both sites and was the only station close to both sites with a record long enough to calculate evaporation and temperature statistics. The evaporation and temperature data show potential evaporation exceeding rainfall for every month of the year. This is cause for concern in crop water use studies as it would affect the soil water crop continuum, thus necessitating proper irrigation scheduling and water application efficiencies for optimum crop yields.

Table 4.1 Monthly climatic information typical of both sites

Month	Rainfall (mm)	A-Pan Evap. (mm)	Monthly means of daily temperatures		
			Maximum (°C)	Minimum (°C)	Average (°C)
January	150.4	180.0	28.1	17.4	22.8
February	121.3	160.0	27.6	17.3	22.5
March	115.4	150.0	27.5	16.0	21.8
April	53.9	120.0	26.3	12.0	19.2
May	23.8	100.0	23.9	6.8	15.4
June	10.0	900.0	22.2	2.6	12.4
July	11.7	100.0	22.9	2.2	12.6
August	32.3	130.0	23.5	5.3	14.4
September	60.1	150.0	24.9	10.0	17.5
October	97.9	160.0	25.1	12.6	18.9
November	120.1	160.0	25.8	14.4	20.1
December	135.1	180.0	27.4	16.2	21.8
Yearly Average	**932.0**	**1680**			**18.3**

4.2.2.2 Monitoring

At field scale the instrumentation installed comprised of one automated recording raingauge (standard tipping bucket raingauge), 12 automated tensiometers, 5 loggers and four piezometer tubes. Irrigated profiles and the off-field control were instrumented at both the Willowfontein and Taylors Halt sites (Figures 4.1 and 4.2). The surface topology at nest 2 of the Willowfontein site and a cross section of instrumentation installation, typical of both sites, is shown in Figure 4.3. All the soil water sensing instruments were made by the School of Bioresources Engineering and Environmental Hydrology (SBEEH). The sections which follow detail the components and installation of these instruments and the monitoring approach used.

Hydrometeorological instrumentation

One standard tipping bucket raingauge (Figures 4.1 and 4.2) was installed by the BEEH school in September 1998 at Willowfontein and in November 1998 at Taylors Halt. This automated recording raingauge was installed on a suitable spot on the edge of the cultivated field. Break point rainfall was recorded with the data being written to a memory module. These data were downloaded monthly. The rainfall data comprised a good data set with no missing records for the period September 1998 to January 1999 for Willowfontein and November 1998 to May 1999 for Taylors Halt.

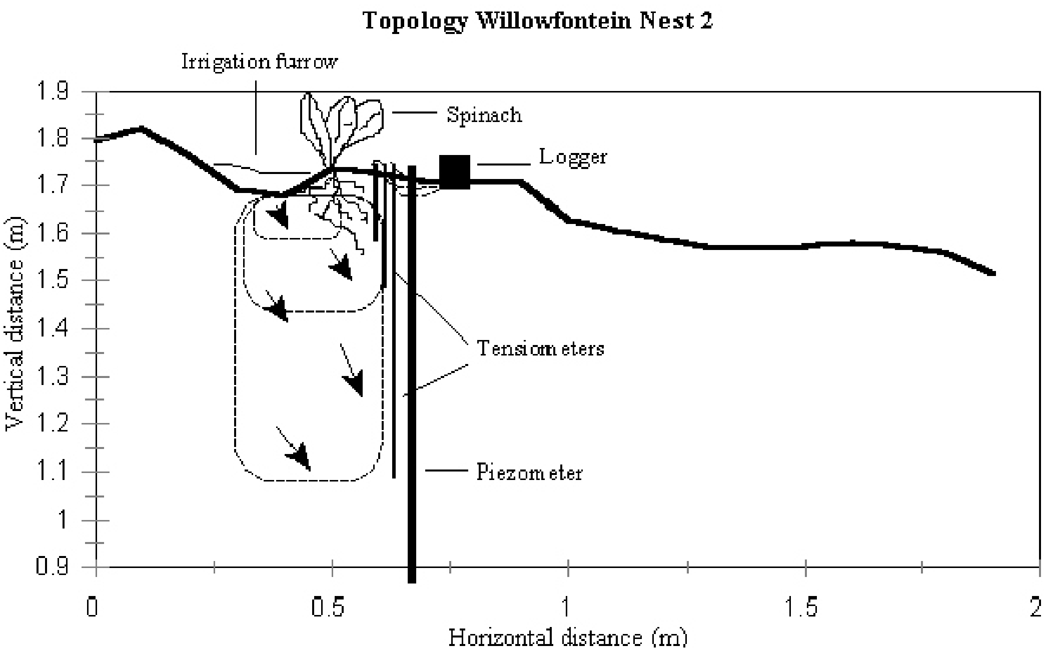


Figure 4.3 Ground surface topology at the Willowfontein, furrow irrigation site, showing a cross section of instrumentation installation, typical of both irrigation gardens.

Soil water monitoring

Tensiometers were installed at both irrigation gardens and were selected for use in this study with the confidence that they have a successful track record for continuous measurement of soil water tension in the field (Ley and Thomas,1994). At each site 4 tensiometer nests were installed at depths ranging from 0.1 to 0.9. Nests 1 to 3 were within the cultivated field while nest 4 the control, was outside the cultivated field in the veld (Figures 4.1 and 4.2). Pressure transducers were connected to each tensiometer and to a four channel logger, which is powered by a 6V battery. Each logger and battery were housed in a tubular protective housing. Soil matric pressure head (refer to 3.2.1) reading were taken every 12 minutes and the tensiometers were serviced with de-aired water every 2 weeks. Ground water piezometers were installed to bedrock depth and manual records were kept of any ground water build-up.

Soil water monitoring was carried out for five months at both Willowfontein and Taylors Halt. The period monitored at Willowfontein extended from August 1998 to December 1998 and at Taylors Halt was from December 1998 to April 1999. Since irrigation is not automated in the conditions monitored in this study, it meant that the cultivators themselves had to record irrigation data. The irrigation data record included the amount of water applied per unit area per irrigation event as well as the date and time of irrigation at Taylors Halt. Cultivators using the furrow irrigation system at Willowfontein recorded the length of time they allowed water to flow along any one furrow before diverting water to the next furrow. The cultivators then gave the recorded data to the researcher. This interaction supplemented the participatory role of the research project.

Soil hydraulic characteristics

Obtaining soil hydraulic properties representative of field soil conditions is important in understanding the dynamic processes of water and solute movement in the soil. Because traditional transient laboratory methods such as outflow or evaporation experiments show relatively little sensitivity to the hydraulic conductivity at near saturated conditions and hence are more suitable for estimating the hydraulic conductivity at medium saturation levels, there is a trend towards determining the hydraulic conductivity in the wet range with steady state experiments, such as the tension disk infiltrometer method or the crust method (Simunek *et al*, 1999). According to Simunek *et al*, 1999, infiltration rates effectively integrate properties of the porous media underneath the disk infiltrometer, including the influence of local scale heterogeneity, different soil structure and texture irregularities, preferential pathways, layering and anisotropy. Infiltration tests to establish saturated hydraulic conductivity, K_s, and unsaturated hydraulic conductivity. K(h), at both Willowfontein and Taylors Halt sites were conducted using the double ring infiltrometer and the tension infiltrometer techniques, respectively.

At both the sites a representative location in the middle of the field was identified and a pit was established. The tension infiltrometer and the double ring infiltrometer tests were carried out at the soil surface and down the profile at increments of approximately 0.30m, to a maximum depth of 2 m. Hydraulic conductivities for both the sites are shown in Appendix C for Taylors Halt and Willowfontein.

Soil samples collected from each soil profile at both the sites were used to characterise the water retension properties of the soil. The method used was the controlled outflow method, described in Lorentz, 1993. This method is used to determine each point on the retention curve by equilibration of the capillary pressure at a fixed saturation. Details of the method and results analysis are described in Lorentz *et al*, 2001. The water retention data together with the hydraulic conductivity data were fitted simultaneously to hydraulic conductivity and water retention functions. The van Genuchten and the Brooks-Corey functions are fitted and the resultant parameters are presented in Appendix C for Taylors Halt and Willowfontein.

4.2.2.3 Modelling of the Irrigation Processes

The 2-Dimensional, soil physics model, HYDRUS-2D (Simunek *et al*, 1994) was used to represent the soil profile at a local scale, beneath and adjacent to the crop and tensiometers nest, in a finite element grid. Specific nodes in the grid where selected as observation nodes at the depths of the tensiometers. No-flow boundary surfaces were designated on the base and sides of the 2-D grid, the top was designated as an atmospheric boundary, except in a ponded irrigation zone. Here, for the Willowfontein case, time dependent pressure heads were imposed to represent the furrow. A typical finite element grid is shown for nest 2 at Willowfontein in Figure 4.4. Initial soil moisture conditions were specified as those from field measured tensiometer data for the three soil horizons. The constant matric pressure head maintained at the base of the profile was 1200 mm, representing a water table 1200 mm below the base of the simulation profile. The root zone was designation by identifying nodes on the finite element grid corresponding to observed root depths and densities. The plant water uptake and stress relationship with soil water status was that of Feddes *et al.* 1974, represented in Figure 4.5.

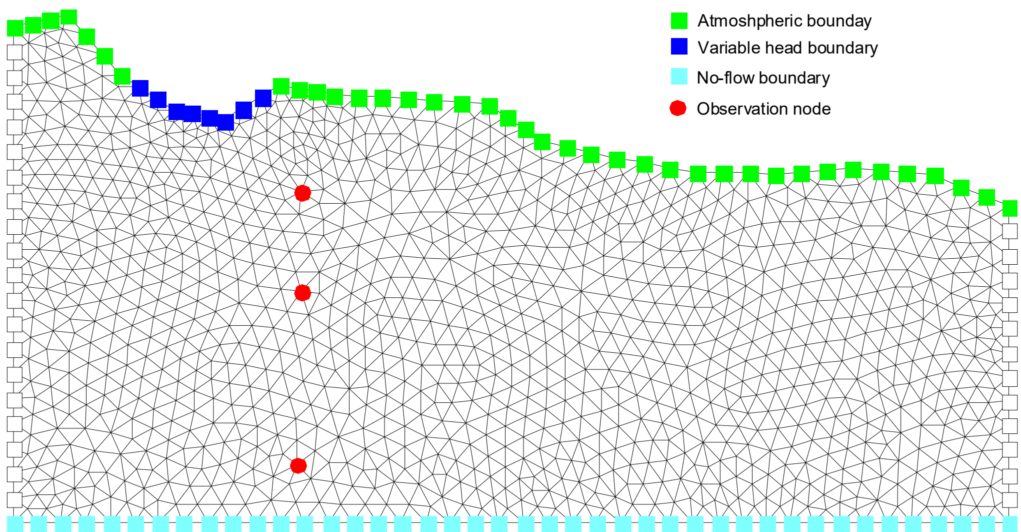


Figure 4.4 HYDRUS-2D finite element grid of the soil profile at nest 2 of the Willowfontein site.

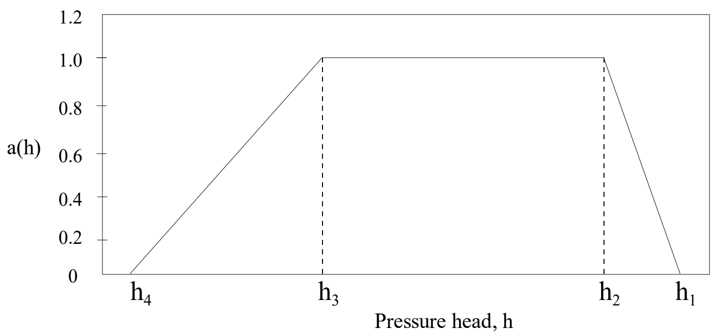


Figure 4.5 Schematic of the plant water stress response function a(h) and soil matric pressure head, h, as used by Feddes *et al*, 1974.

4.3 Results

Results are presented here of the social structures of the two irrigation groups, especially where these structures impact on the methodologies of irrigation. Results are primarily reported on the technical study of the irrigation application, the definition of the processes and the evaluation using simulation modelling.

4.3.1 The Social System

4.3.1.1 Willowfontein

The Willowfontein group, named Sizanani 1, (Sizanani means people working together as a unit to help one another), comprises 25 member, only 5 of whom are male. The group is well organised, with committee, constitution, joining fee (R20), monthly contribution fee (R10) and operating rules. An area of about 0.7 ha is fenced, the land having been allocated to the group by the Willowfontein Development Committee under the auspices of the Pietermaritzburg Transitional Local Council. This area is subdivided into subplots of some 20 m x 30 m and each subplot belongs to an individual member of the group. A water supply channel was constructed from the pre-existing dam into the irrigated vegetable garden. Water from the dam is directed along this channel into the garden during irrigation. This channel is at the top part of the garden and runs parallel to the fence at the bottom section of the garden. An in-field main channel intersects the water supply channel, (Figure 4.1). During irrigation, water is diverted along the furrows from this in-field main channel to irrigate the various sub-plots according to the irrigation requirements of the irrigators. Excess water running on the water supply channel is led off into the small stream on the west side of the garden. The garden committee is responsible for the allocation of sub-plots to members of the group. There are no hard and fast rules as to who should be allocated a plot at the top part of the garden closer to the water supply channel, or at the bottom part of the garden which is quite removed from the water supply channel. During low flows, in winter, the position of the cultivator's sub-plot from the water supply channel significantly influence the efficiency of irrigation. This is because during low flows, the amount of irrigation water reaching the bottom part of the garden is less than that reaching sub-plots closer to the main channel at the top part of the garden. After a series of disputes over irrigation water during the winter season, the cultivators realised that they needed a solution to this problem of uneven distribution of water during the winter season. To resolve the conflict they agreed on the general principle that water be allocated on the first come, first served basis. This principle of water allocation eliminated the advantage that some cultivators enjoyed over others. Over time they decided to adopt this rotational system based on early arrival to the field for both summer and winter seasons. However, due to the surplus of water in summer, more than two cultivators can irrigate at any one time, whereas in winter, a maximum of only two cultivators can irrigate simultaneously.

Allocation of sub-plots is done at random. Observations made during the course of this study were that some sub-plots were left fallow for the entire season. The explanation given was that some members give up participation in the gardening activity for better employment elsewhere and, given that the gardening group committee did not enjoy sufficient powers to re-allocate abandoned sub-plots, these sub-plots were left unattended for a long time. It was indicated that the Willowfontein Development Committee was the body with sufficient powers to resolve matters such as abandoned sub-plots.

When this study was carried out, cultivators at Willowfontein were not aware of any upstream or downstream users except that the dam was also a source of drinking water for stock that belonged to some community members.

Since cultivators at Willowfontein do not experience severe water shortages throughout the year, they have no plans of harvesting water during the rainy summer season. An interesting observation they highlighted was that after a low intensity rainfall event lasting for a maximum of six hours, crops show more life than they do after an irrigation event. Their explanation was that during such a rainfall event crops receive sufficient water covering the entire root zone, they maintained that that was not the case with the furrow irrigation system they were using, which had to last for a relatively short while to prevent the crops becoming stressed as a result of water logging. This observation has made cultivators aspire to install water pipes and sprinklers as one of their immediate plans should they secure funding. They expressed the belief that the installation of such a system would increase water application efficiencies relative to transmission losses currently experienced from the water supply and in-field main channel.

4.3.1.2 Taylors Halt

The Taylors Halt group, named the Nhlanhleni Farmers, (Nhlanhleni means the lucky ones), comprise 18 members, 2 of whom are male. They are also well organised with committee, constitution, joining fee, (R20), monthly contribution fee, (R10) and operating rules. The Taylors Halt site is a community vegetable garden of approximately 0.5 ha in extent, the land having been allocated to the group by the chief. At the bottom part of the vegetable garden located on a north facing hillslope with average gradient of 11%, is a non perennial stream which is the source of irrigation water (Figure 4.2). This stream poses serious irrigation problems in winter when it runs dry. It is for this reason that very little or no gardening activity takes place in the dry winter season. The residents in this area are heavily reliant on the produce from the community garden for vegetables. The commitment they display and the amount of time and effort they put into their gardening activity is clear evidence of this fact. All the members of the group own the same size sub-plots, which run up the slope from the stream at the bottom of the garden to the top part of the garden. This layout ensures that there are no complaints about cultivators enjoying shorter distances between their subplots and the source of irrigation water.

During irrigation, water is collected from the stream using buckets. It is then carried to the irrigated sub-plots and smaller quantities of water are applied from these buckets to the crop. The amount of water applied per crop per irrigation event is approximately 18 mm. Irrigation is carried out in the afternoon and early in the morning in summer. In winter, when it is possible, cultivators irrigate early in the morning so as to reduce the effects of frost on the crops. There are no rules governing water use and allocation at Taylors Halt, save to say cultivators are expected to irrigate their crops sufficiently, such that they do not show any signs of being stressed, especially in summer when there is enough water to irrigate. The cultivators pointed out that they have had no conflicts over irrigation water by the members of the garden group ever since the project was established. They maintained that his was largely due to the fact that each cultivator collects his/her own water and there is sufficient water for all the members to irrigate during the summer season. At the time of conducting this study, the cultivators had no knowledge of any upstream users but mentioned that downstream users used this water only for non-consumable domestic purposes such as laundry. The problem of water shortage in winter affects both the irrigators and the domestic users at Taylors Halt. It is precisely to solve this problem of water shortage in winter that cultivators would like to harvest rain water. Harvested water would be used for irrigation and other domestic purposes. If funds become available they would also like to install a sprinkler irrigation system. This according to them requires less labour than the system currently being used and would make sufficient water available for the crop after each irrigation event.

At the Taylors Halt site not a single sub-plot was left fallow when others had crops growing on them. Also the entire garden was managed as if it belonged to one individual. The reason for this uniformity was attributed to the strict rules governing operations of the group and to the strictness of the chairperson who ensures the enforcement of these rules. The chairperson is also regarded by the rest of the members to be the most influential person of the group. Cultivators agree at their meetings as to which crops to grow, when to irrigate and when to remove weeds. Any member of the group deviating from the agreements reached could be expelled from the group. If for some reason a sub-plot is abandoned by its owner, it immediately becomes the responsibility of the group members to work on that plot collectively, revenue generated from the sale of the produce from that plot is deposited in the group’s banking account, and does not accrue to individual members.

4.3.2 The Technical system

4.3.2.1 Soil characteristics

A full set of the physical and hydraulic characteristics of the soils are presented in Appendix C. The soils at Willowfontein display a marked spatial variation of surface hydraulic conductivities measured at 5 mm tension, ranging from 120 mm/h at the control nest 1 to 4.3 mm/h at nest 4. The range is not as significant at Taylors Halt, (23 mm/h to 13.3 mm/h). The soils at Willowfontein have a higher surface bulk density (1332 kg/m^3) than those at Taylors Halt (897 kg/m^3). At both irrigation sites the densities increase with depth, but nowhere are those at Taylors Halt greater than those at Willowfontein. This phenomenon is reflected in the hydraulic characteristics as shown for Willowfontein in Figure 4.6 and for Taylors Halt in Figure 4.7.

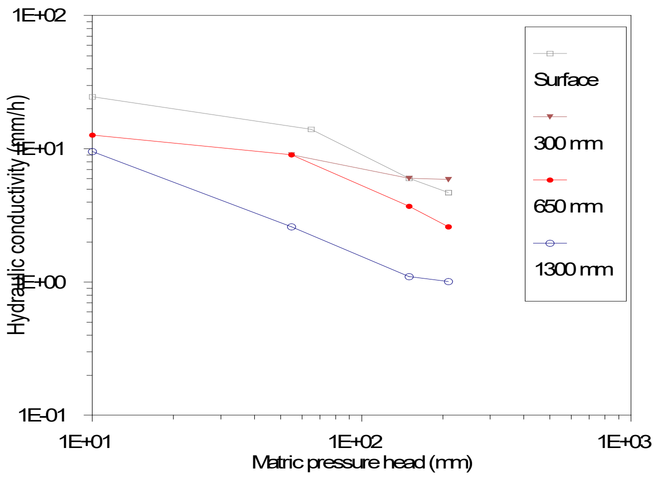


Figure 4.6 Hydraulic conductivities for the Willowfontein profile. (The double ring infiltrometer, saturated hydraulic conductivity is plotted at a matric pressure head: 10 mm)

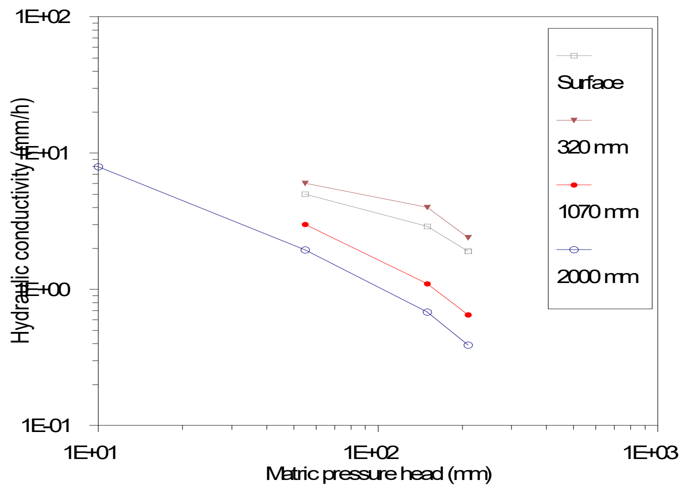


Figure 4.7 Hydraulic conductivities for the Taylors Halt profile. (The double ring infiltrometer, saturated hydraulic conductivity is plotted at a matric pressure head: 10 mm)

Again, there is a decrease in hydraulic conductivity with depth at both sites, but the unsaturated hydraulic conductivities at Taylors Halt are generally lower than those at Willowfontein. This could be because the looser structure at Taylors Halt results in significant macropore channels and so the ponded hydraulic conductivities at Taylors Halt are higher, but the unsaturated conductivities of the remaining matrix are lower. Some measurements of saturated hydraulic conductivity at Taylors Halt wereas high as 1400 mm/h and 132 mm/h.

The water retention characteristics are summarised in Appendix C. The drained upper limit of the Willowfontein soils are lower than those for Taylors Halt, reflecting the large porosity and water retention capablilty of the Taylors Halt soils. Wilting point estimates from the retention characteristics measured in the lab are similar for both sites.

The parameters of the characteristic functions, fitted to the retention and hydraulic conductivity data simultaneously, are listed in Appendix C.

4.3.2.2 Observed data

The matric pressure head data were recorded for Willowfontein from August 1998 to December 1998 and for Taylors Halt from December 1998 to April 1999. Example data sets are presented in Figures 4.8 and 4.9. The interpretation of these figures is explained in section 3.2.1 of this report.

Willowfontein

The matric pressure head and rainfall data for Willowfontein, nest 2, are shown for 16 October 1998 to 20 November 1999 in Figure 4.8. A minor rainfall event of6 mm on 20 October 1998, (event A in Figure 4.8), did not cause a response in the tensiometers at any level. This minor event was considered by the irrigator to be insufficient to satisfy the crop demand but irrigation event B was applied on crops at nest 1 and 2 during that day. This and subsequent irrigation events C, D and E all caused a drop in matric pressure head (wetting) at the 0.19 m and at the 0.37 m level. Of significance is the interval between irrigations and the length of time during which water was allowed to flow along the furrow. During event B, the irrigator allowed 30 minutes of furrow inundation, but during event C, 6 days later, the application was only 15 minutes, although the same irrigator allowed 30 minutes of furrow application in nest 1 in event C. Event E was applied 7 days later for a period of only 10 minutes which resulted in the smallest drop in matric pressure head at the 0.19 m level. Even at the 0.37 m level, the drop in matric pressure is the smallest of the record. The rapid increase in the matric pressure head at the 0.19 m and 0.37 m levels after event E is indicative of the shallow wetting and small volume of water in the profile. Event F is a rainfall event which causes a drop in the near surface, 0.19 m matric pressure head, but very little response from deeper tensiometers. These inconsistencies in timing and application of irrigation water can be construed as poor irrigation scheduling. However, simulating current practices as well as an alternate application scheduling will show that a more efficient and effective irrigation schedule is possible.

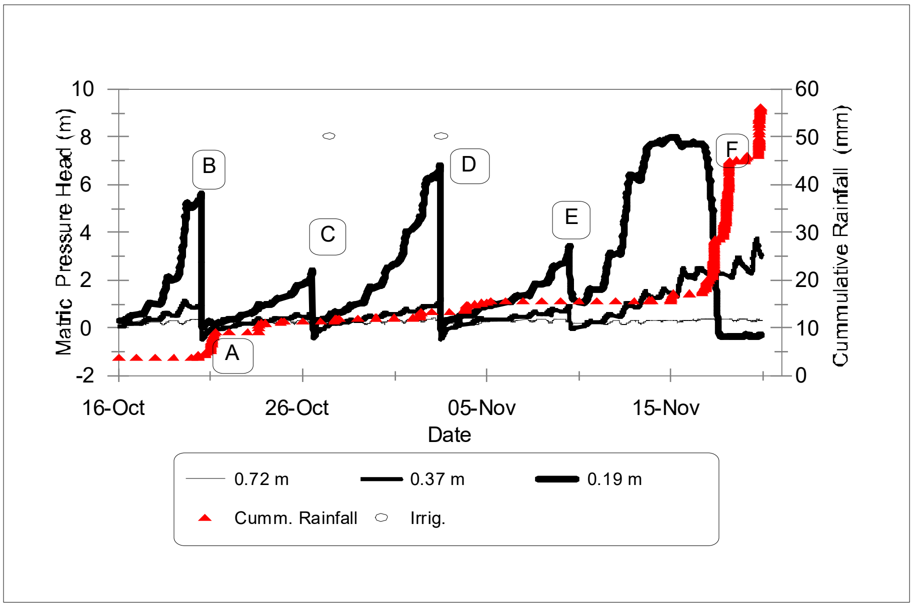


Figure 4.8 Rainfall and matric pressure head history for Willowfontein, nest 2, between 16 October 1998 and 20 November 1998. Rainfall events A and F and irrigation events B to E are indicated.

Taylors Halt

An example of the Taylors Halt , nest 1data from 18 March to 31 March 1999 is shown in Figure 4.9. This period was relatively wet, being during the rain season. Event J causes a significant drop in matric pressure head at all levels. Irrigation water was applied daily before and after this event. No noticeable drops in matric pressure head are evident at the time of application. In fact, the matric pressure head at the 0.2 m and 0.47 m levels climb steadily, but not as rapidly as at Willowfontein. Diurnal fluctuation caused by temperature variations in the tensiometer liquid should not be confused with responses to irrigation. Despite this slow climb in matric pressure head, the profile is considerably wetter than the control plot during the same period. This indicates that the irrigation applications are effective in keeping the profile moist. Irrigators even applying water when the the matric pressure head in the upper layers was less than 1.0 m (events K and L).

At the Willowfontein site there was no observable water table at the depth of installation of the observation tube at 1.9 m. At Taylors Halt where once-off augering for ground water occurred at the end of the monitoring period, ground water was located at 5.0 m below surface some 12 m from the stream.

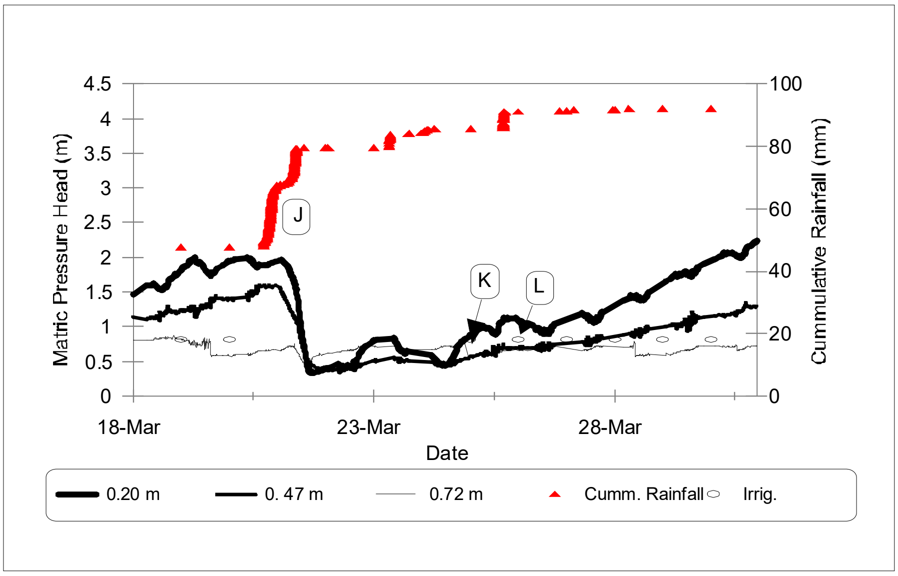


Figure 4.9 Rainfall and matric pressure head history for Taylors Halt, nest 1, between 18 and 31 March 1999. Rainfall event J and irrigation events K and L are indicated.

4.4 **Modelling Results**

4.4.1 Willowfontein

Simulated time series of the observation nodes are compared to the observed matric pressure head record at the 0.19 m and 0.72 m level in Figures 4.10a and 4.10b, respectively. The matric pressure heads are simulated accurately for the upper horizon at 0.19 m (Figure 4.10a), as is the case for the 0.37 m level. However, the simulated matric pressure heads are slightly lower (wetter) than those observed at the 0.72 m level. This is attributed to the no-flow bottom boundary condition, allowing for some accumulation of water in the deeper horizon of the simulated scenario. However the zone where the root uptake occurs is adequately simulated and useful for comparing alternate irrigation strategies.

With the observed data adequately simulated, alternate irrigation strategies to optimise crop water use, were devised. The scenario involved increasing the frequency of application and reducing the amount applied per irrigation event. The results of the simulated matric pressure heads at the 0.19 m level are shown in Figure 4.10c. Since the crops studied had a maximum root water uptake between matric pressure heads of 0.1 m and 3.2 m, unnecessary drainage had been taking place with the large application rates, resulting from 30 minutes of furrow flow. In the simulated, efficient scenario, the irrigations are 15 minutes and are applied more frequently. It can be seen that the profile near the surface dries up rapidly, but at no time is the crop under stress.

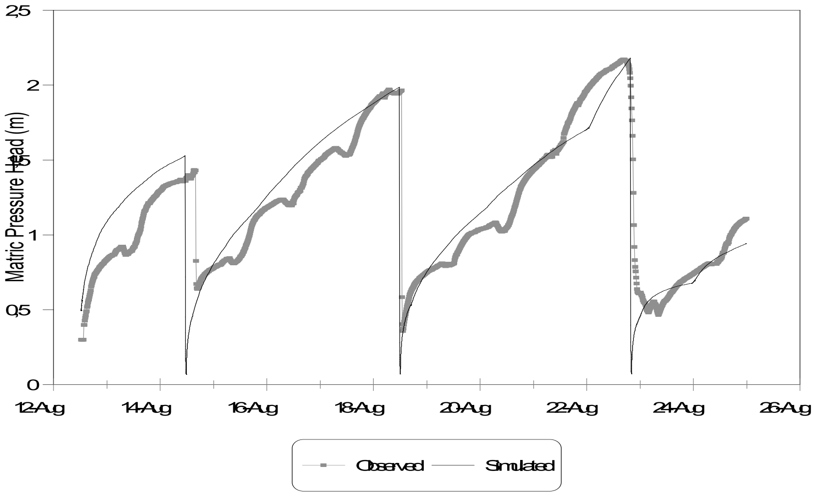


Figure 4.10a. Simulated versus observed matric pressure head at 0.19 m at nest 2, Willowfontein.

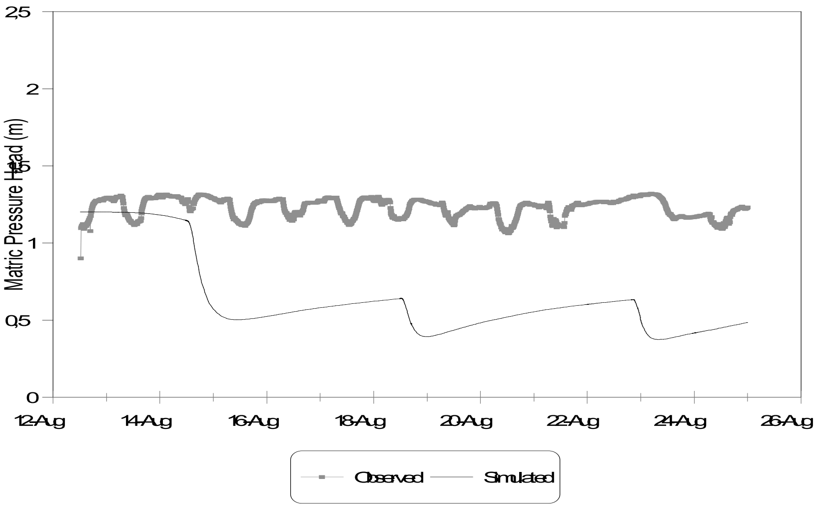


Figure 4.10b. Simulated versus observed matric pressure head at 0.72 m at nest 2, Willowfontein.

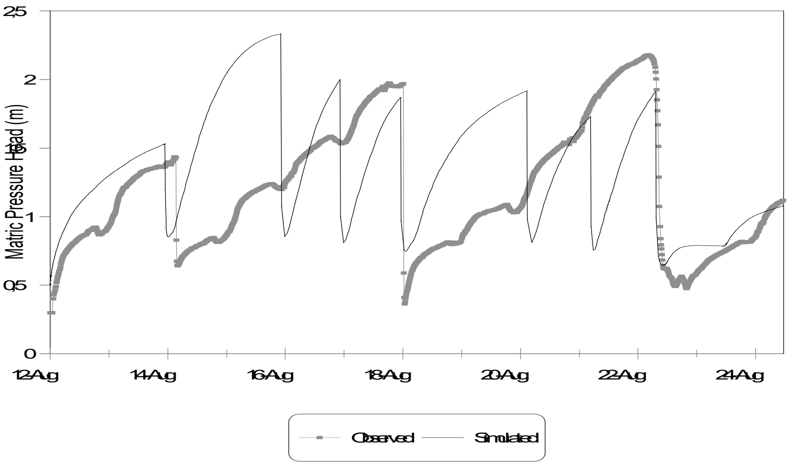


Figure 4.10c. Simulated efficient scenario versus

observed matric pressure head at 0.19 m at nest 2, Willowfontein.

The simulated flux of water draining past the 0.65 m level, (below the root zone) is compared for the current and proposed irrigation strategies in Figure 4.11. Pronounced changes in the flow of water below the root zone are noticeable from current irrigation strategy. The proposed efficient strategy results in a constant flux below the root zone, without sever loss during irrigation periods. The proposed strategy improves the amount of water lost to drainage by 115 mm for the period simulated. Nevertheless, this still allows sufficient drainage preventing any salt build-up. Graphical representations of the distribution of the water content in the profile during irrigation are shown for Willowfontein in Appendix D.

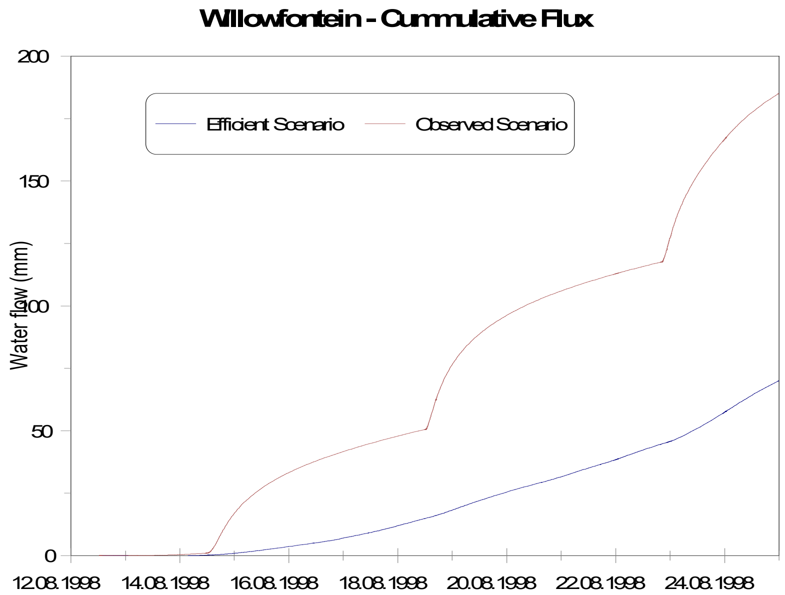
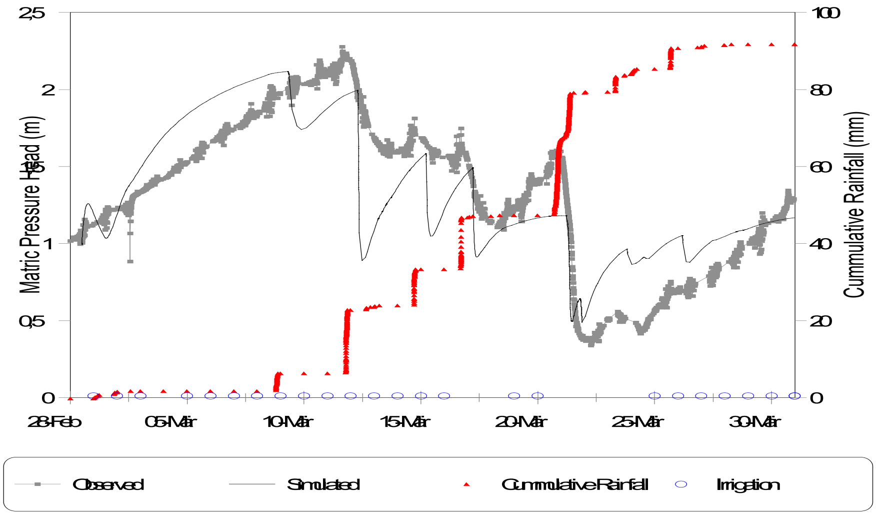


Figure 4.11 Comparison of simulated cumulative flow below the root zone for the observed irrigation strategy and a proposed efficient strategy for nest 2 at Willowfontein.

Taylors Halt

A time series of matric pressure head for simulated and observed current irrigation practice is shown in Figure 4.12a for the 0.2 m level and in Figure 4.12b for the 0.72 m level, Both levels are accurately simulated by the model. The simulated results respond adequately to the rainfall and, as with the observed matric pressure head, very little response is observed due to the 18 mm of water applied daily by the irrigators. Nevertheless the model faithfully predicts the slower drying rate caused by the irrigation.

The efficiency of reducing the number of irrigation applications, allowing the matric pressure heads to increase to acceptable levels before further application, is studied using simulations. Crops at Taylors Halt had a maximum root water uptake between matric pressure heads of 0.25 m and 3.2 m, with stress being initiated outside of these limits. The current observed data show no period in which the soil water matric pressure heads in the root zone reached the upper limit. Unlike at Willowfontein, where cultivators



use their intuition to identify times for irrigation, at Taylors Halt the frequency of irrigation seems to be determined by rigid adherence to prescribed rules. The matric pressure head history for the proposed efficient scenario is shown in Figure 4.12c, showing the matric pressure heads increasing between irrigations.

Figure 4.12a. Simulated and observed matric pressure heads for current practice at Taylors Halt, nest 1 at a depth of 0.2 m.

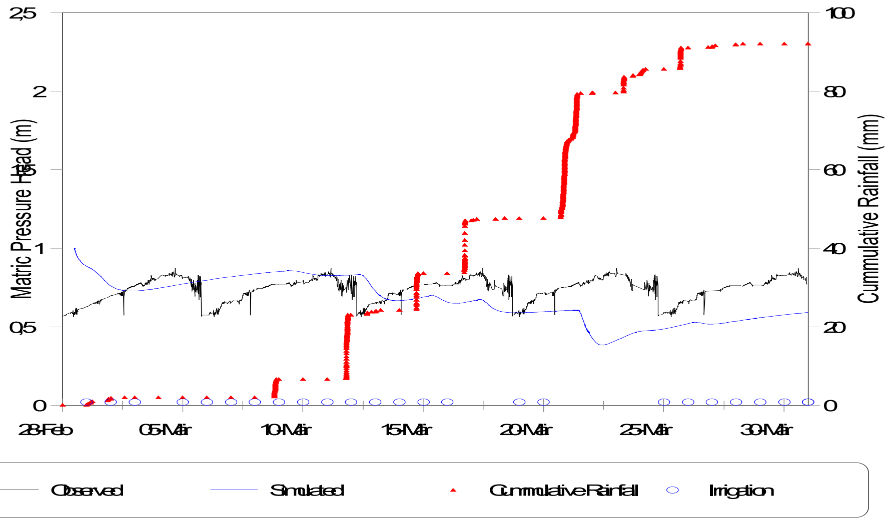


Figure 4.12b. Simulated and observed matric pressure heads for current practice at Taylors Halt, nest 1 at a depth of 0.72 m.

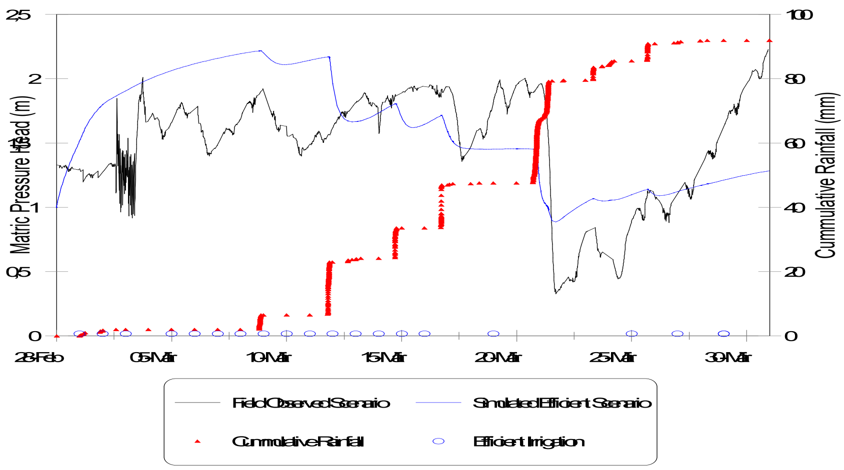


Figure 4.12c. Simulated proposed efficient scenario and observed matric pressure heads at Taylors Halt, nest 1 at a depth of 0.2 m.

The flux below the root zone is, again, considerably reduced by applying the proposed efficient irrigation strategy. The cumulative drainage below the root zone is shown in Figure 4.13 and indicates a reduction in drainage water of some 80 mm during the period analysed.

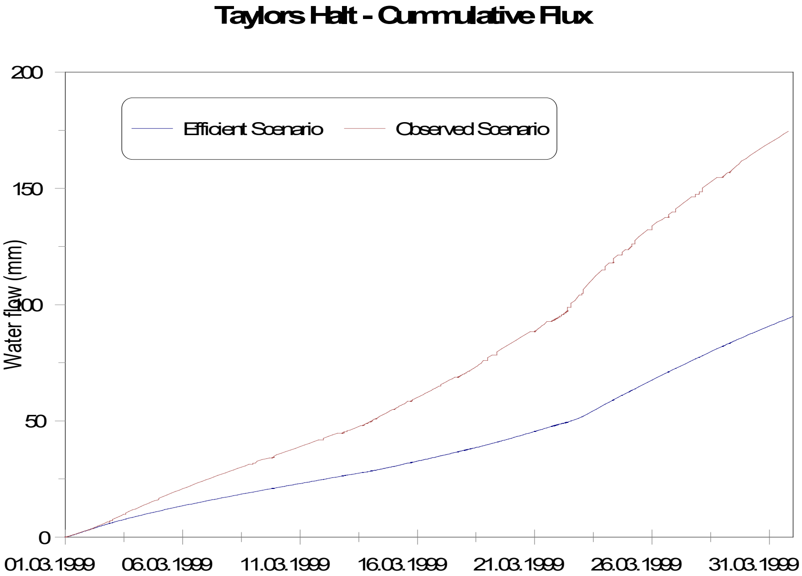


Figure 4.13 Comparison of simulated cumulative flow below the root zone for the observed irrigation strategy and a proposed efficient strategy for nest 1 at Taylors Halt.

4.5 Conclusions and Recommendations

The significant result of this study has been the demonstration of the use of reasonably inexpensive, but sophisticated measuring techniques to observe the soil water processes in small scale gardening practices. These observations led to accurate simulations of the soil water infiltration, redistribution and uptake in 2 dimensions. With these successful simulations, more efficient irrigation scenarios were proposed and evaluated.

It can be concluded that:

- Automated tensiometers and raingauges, with simple recording of irrigation application timing and duration were critical for the observation and definition of soil water processes in small scale irrigation.
- The effects of over irrigation, infrequent or too frequent application were easily detectable by evaluating the record of matric pressure head data for different levels.
- Simulation of the soil matric pressure head history faithfully reproduced the dominant effects of

the current irrigation practice.

- Once the model had been successfully verified against observed data, scenarios of more efficient application were produced and the soil water processes evaluated.

- At Willowfontein, a more frequent application of smaller amounts of furrow irrigation was found to be a more efficient use of the water, resulting in a reduction in drainage below the root zone of 115 mm over a period of one month.

- At Taylors Halt, a less frequent application of similar amounts of hand irrigation was found to be a more efficient use of the water, resulting in a reduction in drainage below the root zone of 80 mm over a period of one month.

Resulting from these observations and simulations, it is recommended that:

- The results are communicated to the Willowfontein and Taylors Halt gardening communities and others involved in similar practices.

- The feasibility of the use of automated soil sensors or other devices in small scale agriculture is investigated with the purpose of optimizing irrigation plant water uptake and source water use.

- The use of simulation modeling be recommended as a tool for evaluating current practices and in devising more efficient strategies in the small scale irrigation industry.

Chapter 6
Conclusions and Recommendations

Simon Lorentz

Selected hydrological processes have been studied, analysed and documented. A detailed description of the comprehensive monitoring network and data base of the School of Bioresources Engineering and Environmental Hydrology is provided.

The mechanisms of hillslope hydrology have been investigated at the research catchment, Weatherley. Here, soil water and ground water sensors, rainfall and runoff data have been used to define dominant mechanisms of runoff generation, redistribution and storage of water in the hillslopes. The implications of modelling these processes at the large catchment scale has been introduced.

In an intensive study of small scale irrigation efficiency, soil water sensors have been used to determine the effectiveness of current irrigation practices. A detailed soil physics model was used successfully to simulate the current conditions. The model was then used to evaluate alternative and more efficient irrigation strategies.

A summary of additional hydrological process studies which have been supported by this project, but which have been reported elsewhere, has also been compiled.

Each chapter contains conclusions of the findings of the particular aspect of hydrological processes described. However, a summary of the more pertinent conclusions is presented here.

6.1 Monitored Data Base

The data base of all monitored catchments and hydrological experiments has been summarised and the components and operation of the data base have been described. It is concluded that:

- There are currently 7 catchment scale monitored areas, many of which have multiple subcatchments and 4 areas of local, field or hillslope scale monitored experiments. Selected data sets of the Weatherley research catchment and the historic Ntabamhlope catchment have been installed in the interactive data base.

- The data, particularly those monitoring the behaviour of subsurface processes are now accessible together with rainfall and runoff data and catchment characteristics.

- The data base is founded on the USGS Generation and Analysis of Model Simulation Scenarios (GenScn) which requires the Watershed Data Management (WDM) format. Nevertheless, primary data files are stored in ASCII format.

- The data base is linked to a GIS system and multiple variables can be retrieved and viewed simultaneously.

It is recommended that:

- The data base is continuously populated with all available and current data from the 7 catchment areas and 4 experimental areas.

- Alternative data bases are periodically reviewed in order to assess the merits of linking the primary data to interactive data bases which can view multiple variables, each of which may be have different time intervals.

6.2 Hillslope Hydrological Processes

Details of the research catchment at Weatherley, northern Eastern Cape Province have been described and the subsurface processes, together with rainfall-runoff responses have been evaluated in order to define the flow mechanisms. The implications of these flow mechanisms on catchment runoff has been deduced and process algorithms for inclusion in catchment scale models have been proposed. It is concluded that:

- The monitoring network of pre-afforestation conditions in the Weatherley catchment has been systematically developed over 5 years.

- Currently monitored in the catchment are:
    - Rainfall and meteorological variables,
    - Runoff at two nested crump,
    - Automatic soil water matric pressure head in 20 profiles,
    - Automatic and manual ground water elevation in 20 observation wells and
    - Manual soil water content by neutron probe measurement at 29 stations.

- Evaluation of these data has revealed that::
    - Rapid lateral flow occurs near the surface due to macro-pore conductance during intense events or events which have large volumes on the upper hillslope sections,
    - Rainfall induced, local perched water tables in the near-surface profile are of short duration (less than 24 hours) and the matric pressure head is discontinuous with the deeper perched water table except in the upstream catchment, where the sandstone layer does not outcrop,
    - There is a rapid increase in the ground water elevation in the flatter, lower slope sections after the commencement of rainfall. Water is supplied to this ground water body from the upper slope and from rapid vertical infiltration through the macropore system in these profiles.,
    - In the upper slopes, the accumulation of water at the toe continues for many days after a rainfall event and, for intense events of significant volume, there is exfiltration over the sandstone outcrop and
    - The contribution of near-surface water to the deeper ground water, perched on the bedrock, during a storm event, is greater for long duration high volume rainfall than it is for short duration, high intensity rainfall.

- Modelling of the profiles with available soil physics or hillslope models clearly lacks the mechanisms of flow generation in perched, near surface water tables as well as the contribution from these macropore layers into the deeper perched water tables.

It is recommended that:

- The rates and timing of the various flow generation mechanisms are further quantified by sampling natural isotopes or natural ion tracers from the various sources,

- The simple algorithm for lateral flow generation for catchment scale models is further developed and tested,

- Cognisance of the flow generating mechanisms need to be taken by practitioners using the hillslopes to conduct agriculture or agroforestry and

- The implications of the timing of the flow generating mechanisms and the storage and release of water observed in the hillslopes needs to be defined for low flow sequences at larger scales.

6.3 Small Scale Irrigation Processes

Two small scale irrigation market gardens have been studied to assess soil water and plant uptake processes in conjunction with the social system of irrigation management in order to define the hydrological processes and assess the irrigation efficiency.

It can be concluded that::

- Automated tensiometers and raingauges, with simple recording of irrigation application timing and duration were critical for the observation and definition of soil water processes in small scale irrigation,

- The effects of over irrigation, infrequent or too frequent application were easily detectable by evaluating the record of matric pressure head data for different levels,

- Once the model had been successfully verified against observed data, scenarios of more efficient application were produced and the consequent soil water processes and drainage evaluated.

It is recommended that::

- The results are communicated to the Willowfontein and Taylors Halt gardening communities and others involved in similar practices,

- The use of automated soil sensors or other devices for assessing water application in small scale agriculture is investigated with the purpose of optimizing irrigation plant water uptake and source water use,

- The use of simulation modeling be recommended as a tool for evaluating current practices and in devising more efficient strategies in the small scale irrigation industry and

- Studies of small scale irrigation practices should include both technical and social evaluations.

6.3 General Hydrological Processes

Contributing area sediment yield processes research is directly linked to the hillslope flow generation research and is continuing in Water Research Commission projects on hillslope hydrology and on agricultural catchments sediment yield.

Soil water processes have been studied in irrigated rehabilitated mined land. Lateral flow and accumulation of water on spoil layers has been identified and modelled. The implications for seepage through the spoil material have been assessed. This research is continuing in a collaborative study supported by the coal mining industry and the Water Research Commission.

Snowmelt routines have been included in the *ACRU* model and tested in German catchments.

Recession curve analyses have been completed in order to develop a rule based definition of base flow contributions to stream flow. It was concluded that until further analysis were forthcoming, the development of a rule based model for baseflow recession analysis in South Africa would be premature. The establishment of a readily accessible database containing streamflows and associated catchment characteristics, however, lends itself to future research in this regard.

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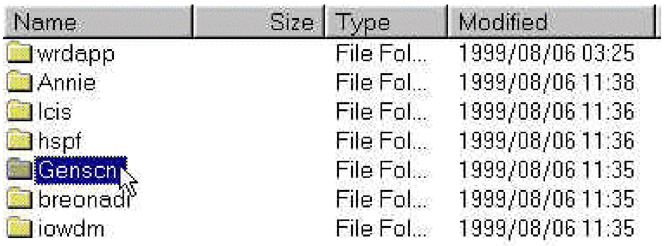
APPENDIX A

RESEARCH CATCHMENTS DATABASE AND INSTALLATION MANUAL

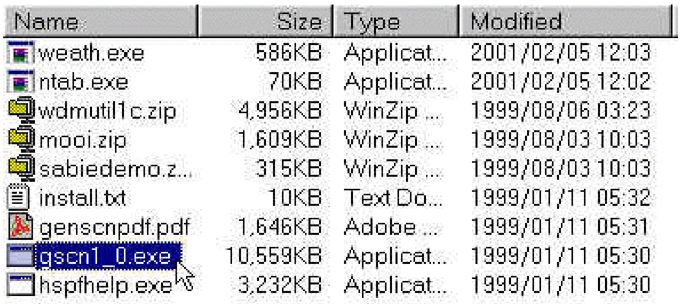
Procedure for the installation of GenScn and the two example data sets.

Step 1: The installation of GenScn.

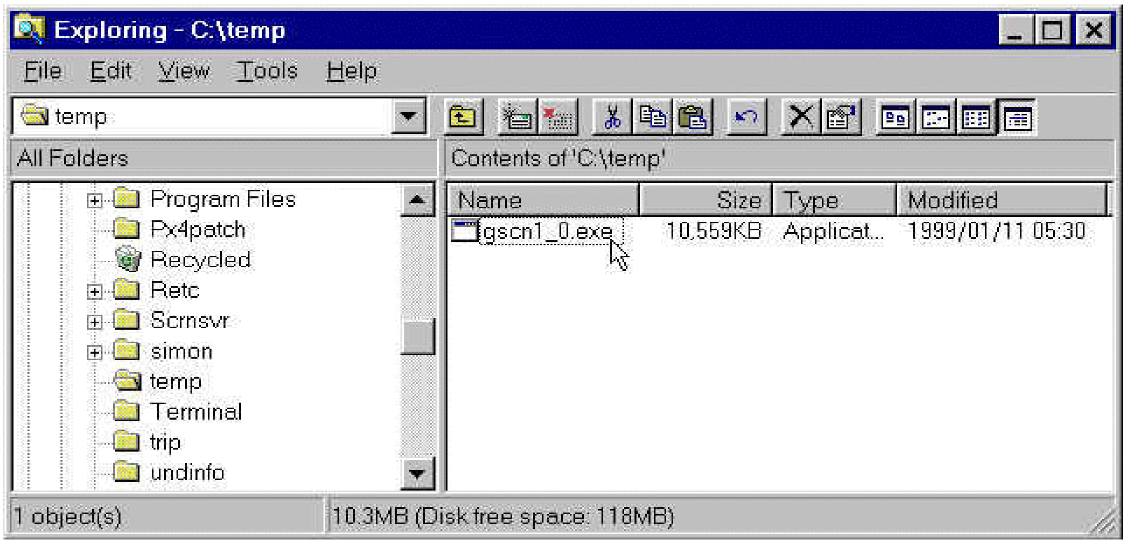
As with any installation it is advisable to first close all programs that are running.
Insert the CD supplied. Select the 'Genscn' directory.



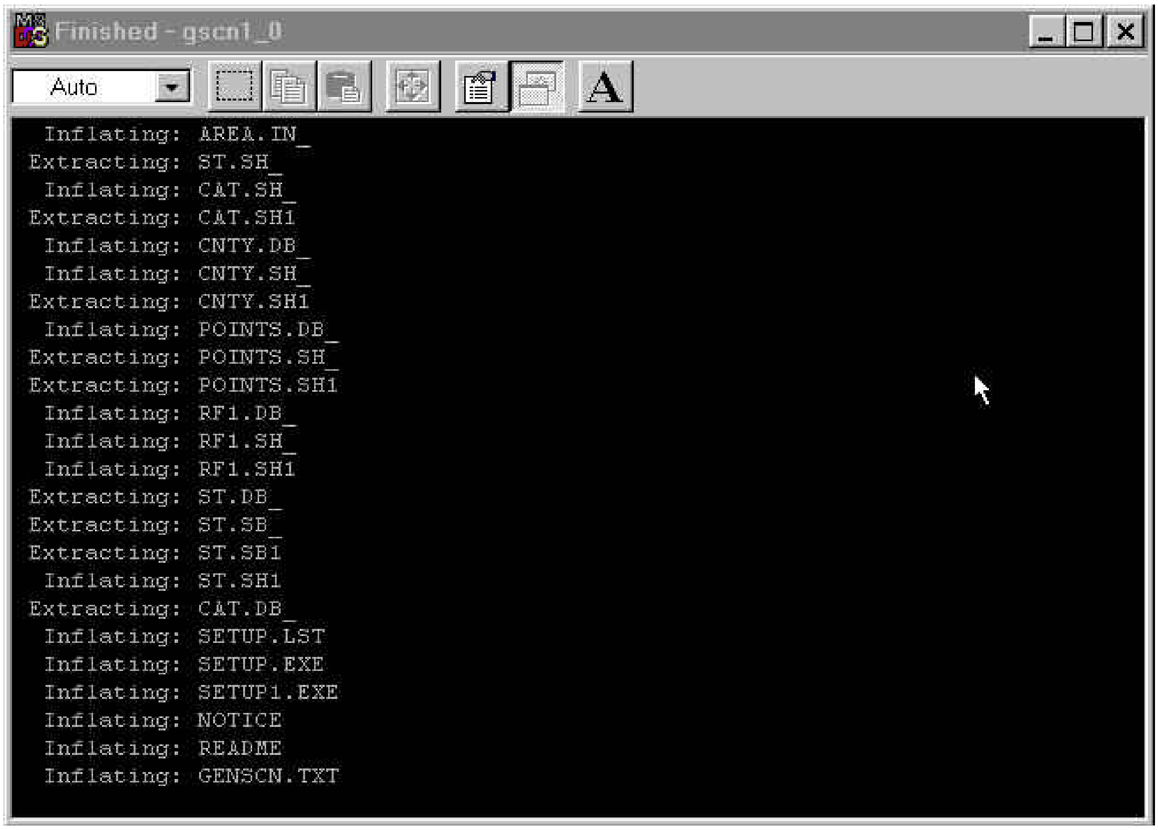
Select the file 'gscn1_0.exe'. Copy this file to a temporary folder on your 'C:\' drive. Say 'C:\temp' for example.



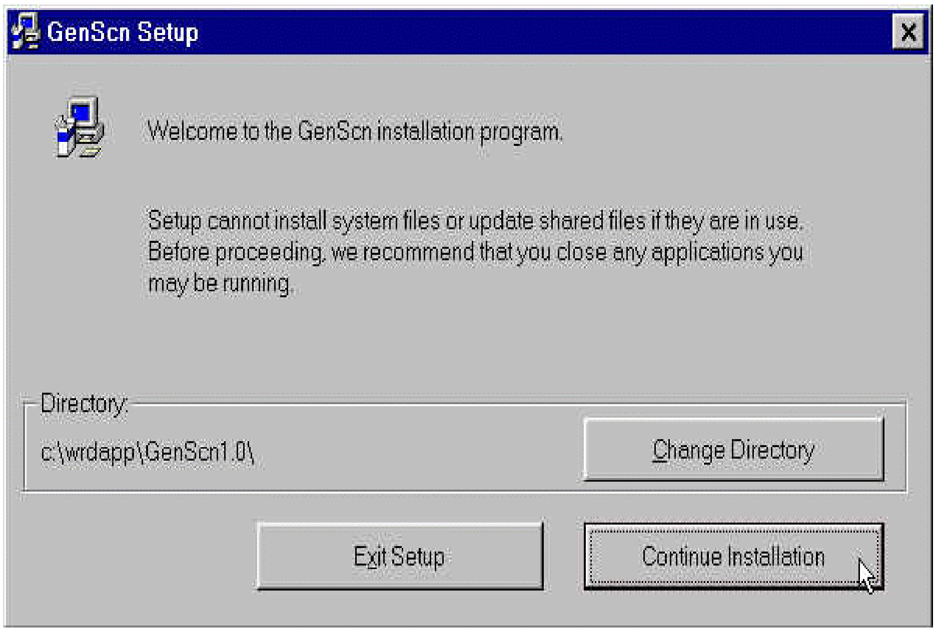
Run the file 'gscn1_0.exe' in the temporary folder that you have created by double clicking on it.



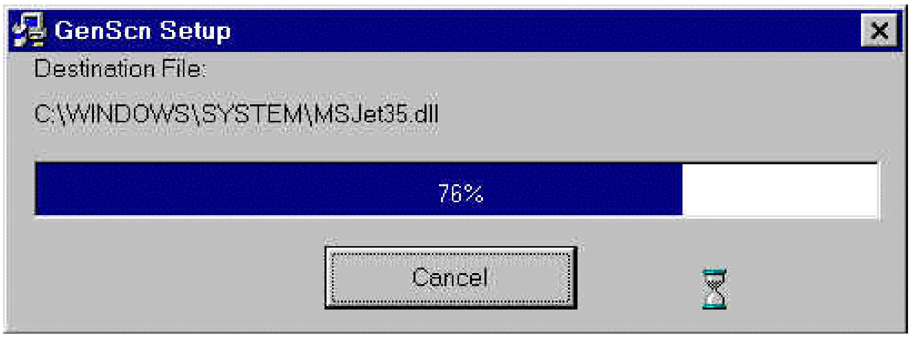
This will expand a number of temporary installation files into this folder.



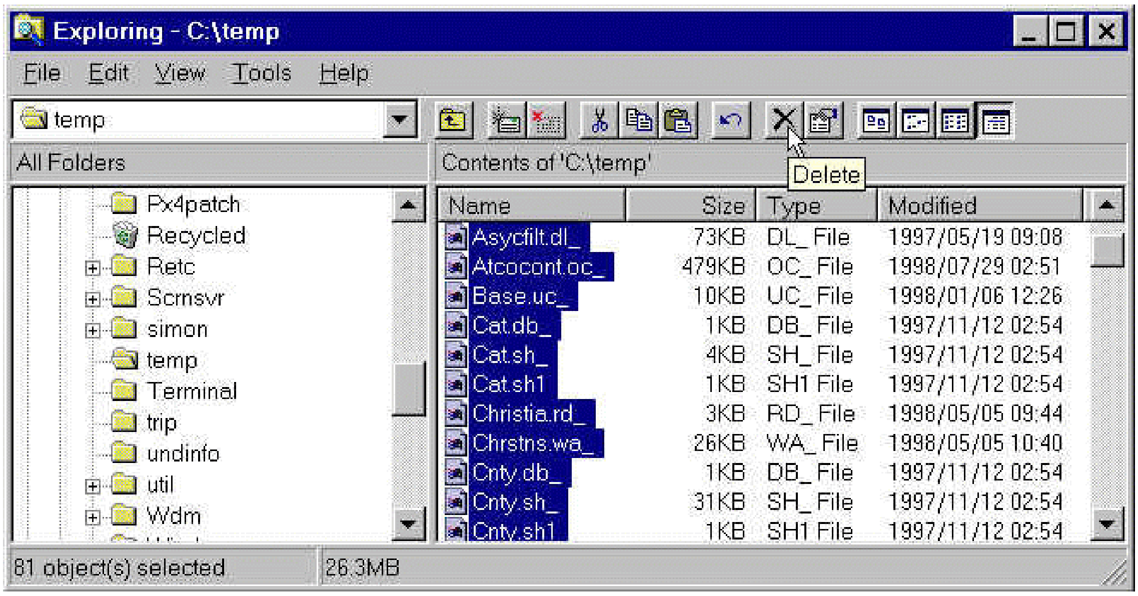
Select and run the file 'Setup.exe' from the one's that have just been extracted to you temporary folder. Be sure that you have selected the correct file as there are two setup files.   Select all the default settings by pressing 'Continue Installation'.



GenScn will be installed onto your computer.

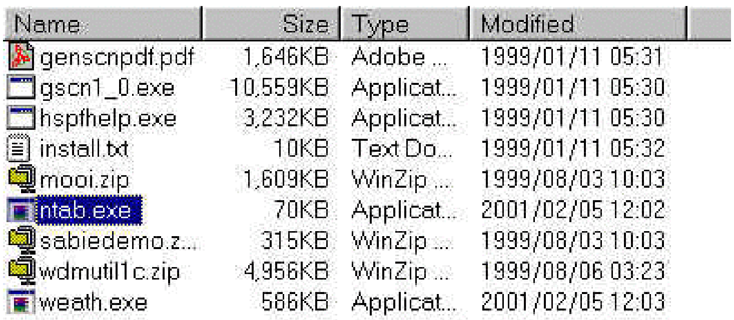


Once the installation is complete you can delete the temporary installation files by selecting all the files in the temporary folder that you created 'C:\temp' and deleting them.

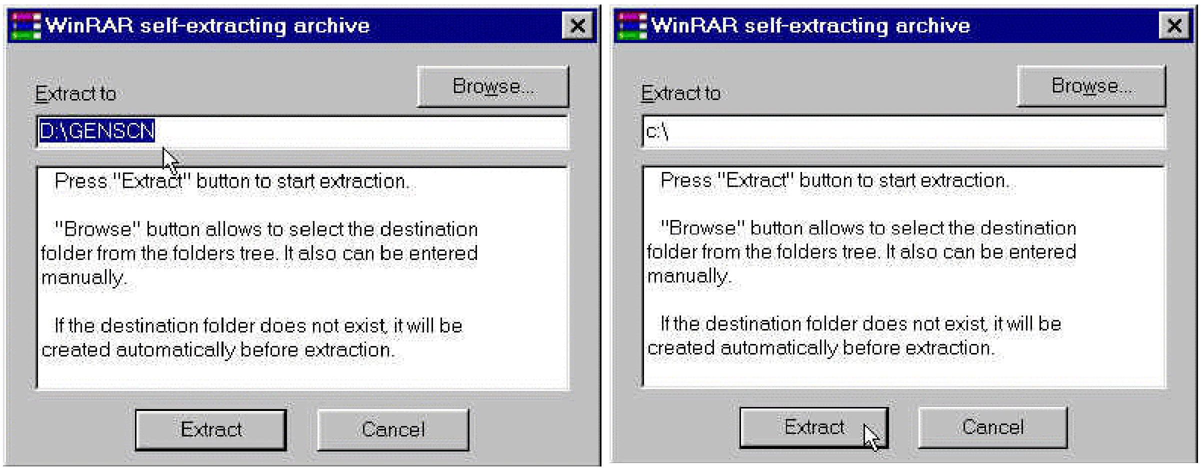


Step 2: The installation of the Ntabamhlope example.

Select and run the file 'ntab.exe' from the 'Genscn' directory on the CD.

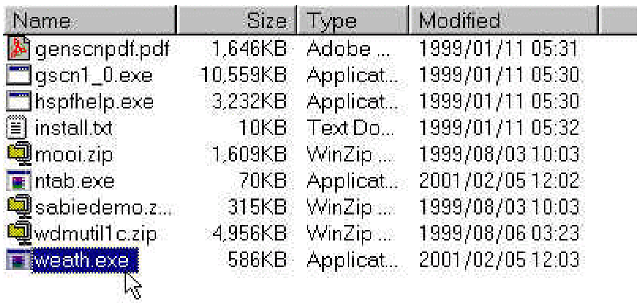


Change the destination to 'C:\' and select 'Extract'. It will then automatically copy the files to 'C:\wrdapp\GenScn1.0\ntab\'.

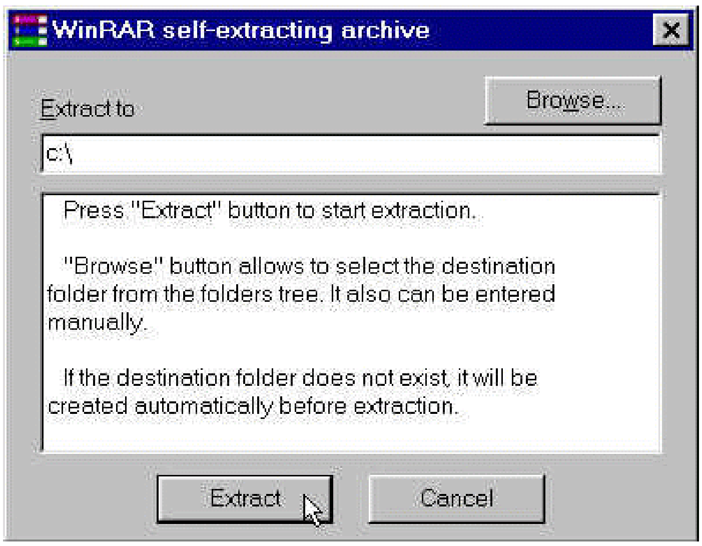


Step 3: The installation of the Weatherly example.

Select and run the file 'weath.exe' from the 'Genscn' directory on the CD.

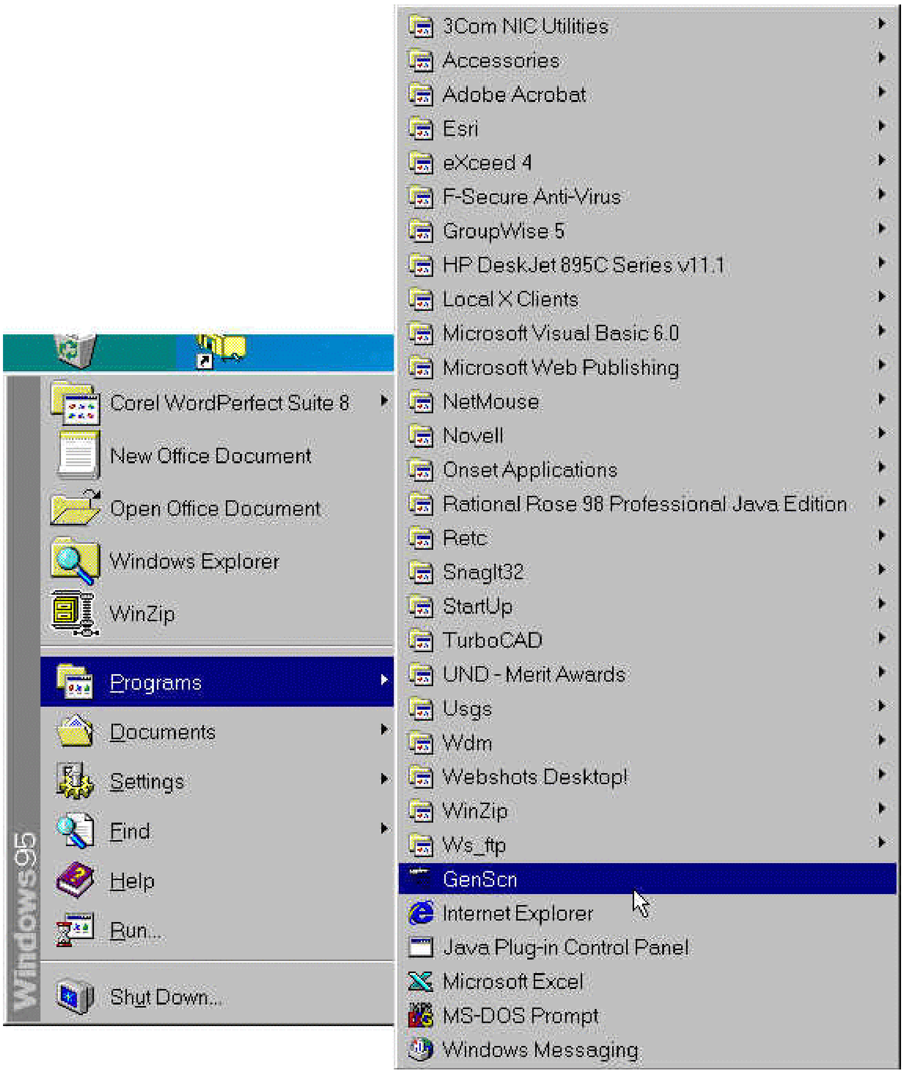


Change the destination to 'C:\' and select 'Extract'. It will then automatically copy the files to 'C:\wrdapp\GenScn1.0\weath\'.

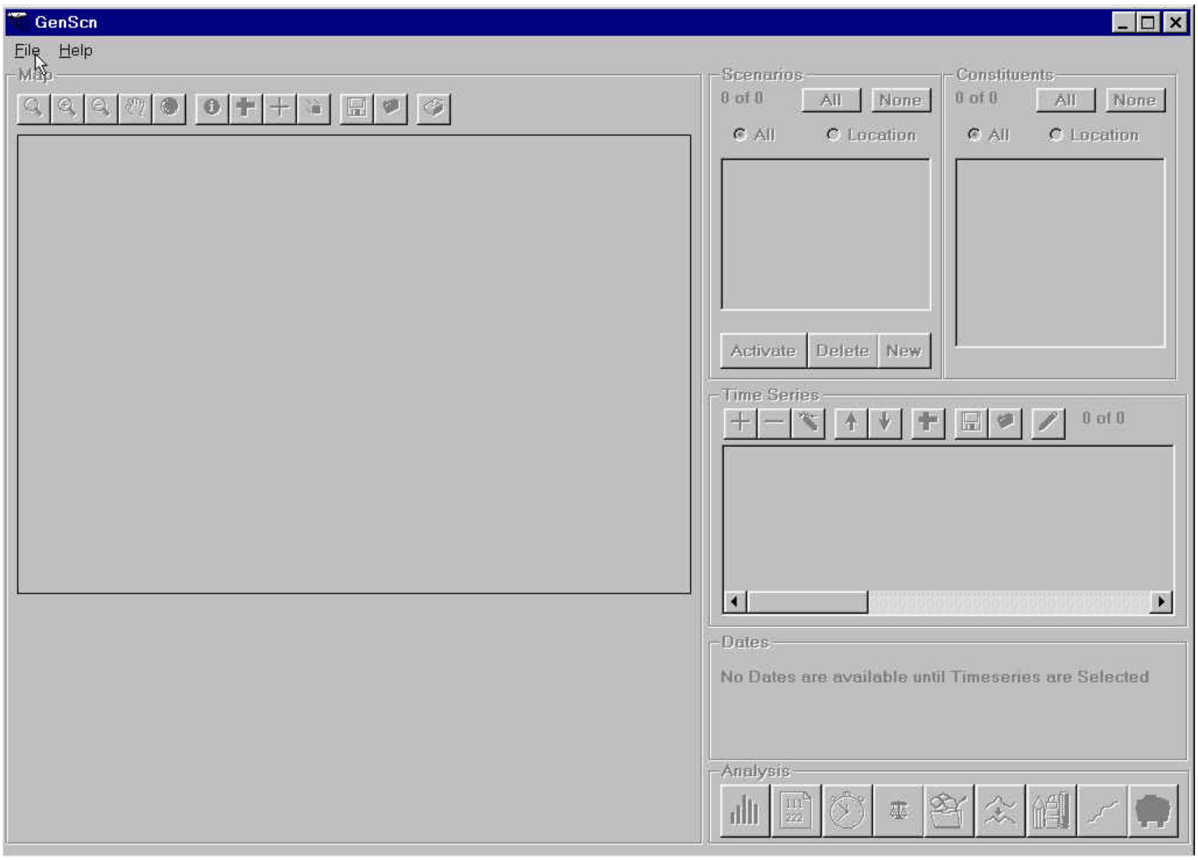


Procedure for running GenScn and the two data set examples .

Select GenScn from the programs menu on the start bar.

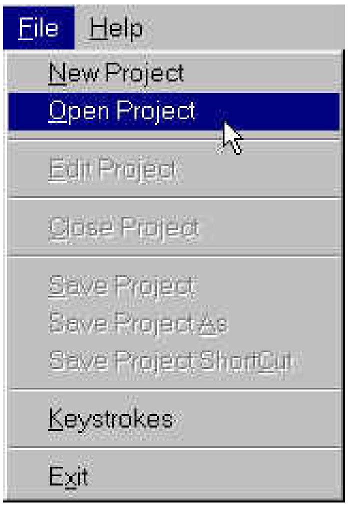


The GenScn interface.

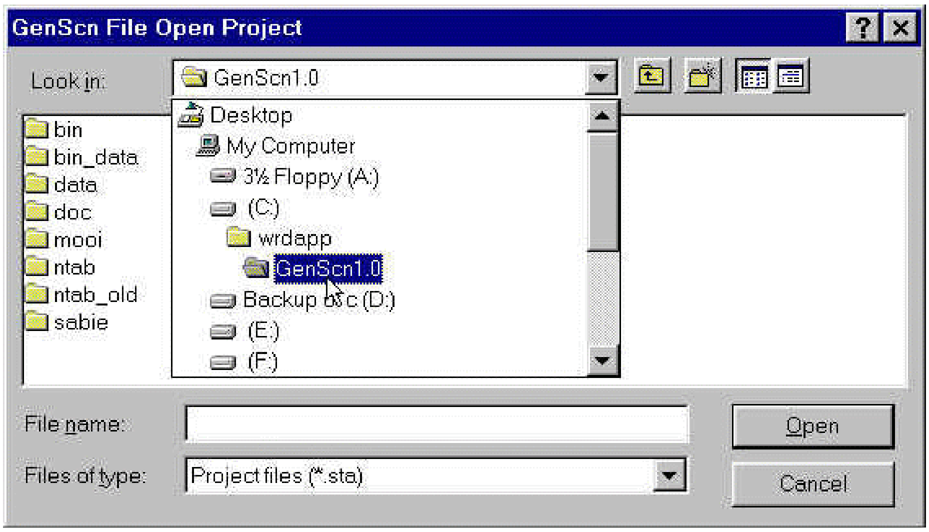


Opening the Ntabamhlope example.

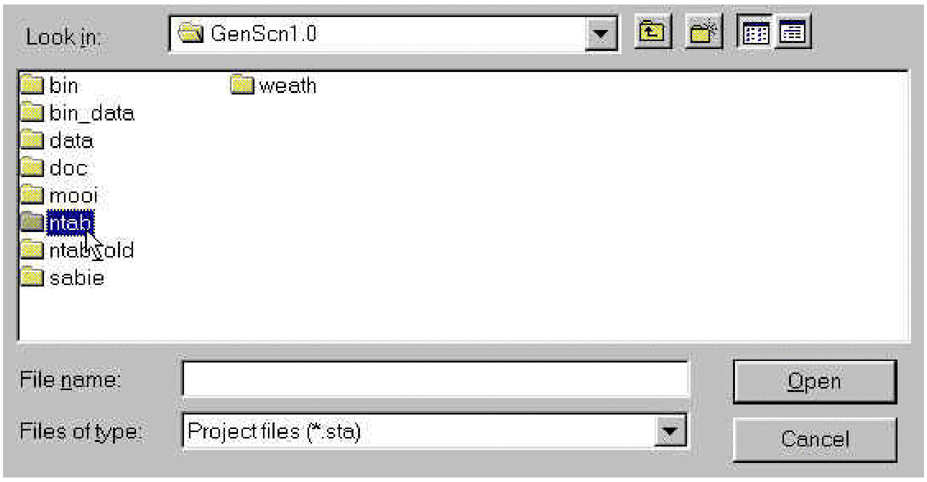
To open the Ntabamhlope example, select ‘file’ then ‘Open Project’.



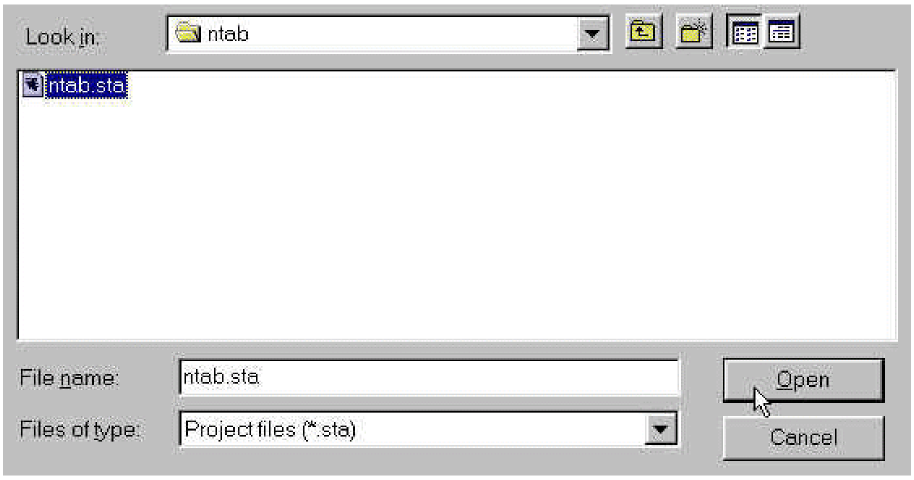
Look for 'C:\wrdapp\GenScn1.0\' directory.



Open the 'ntab' folder.

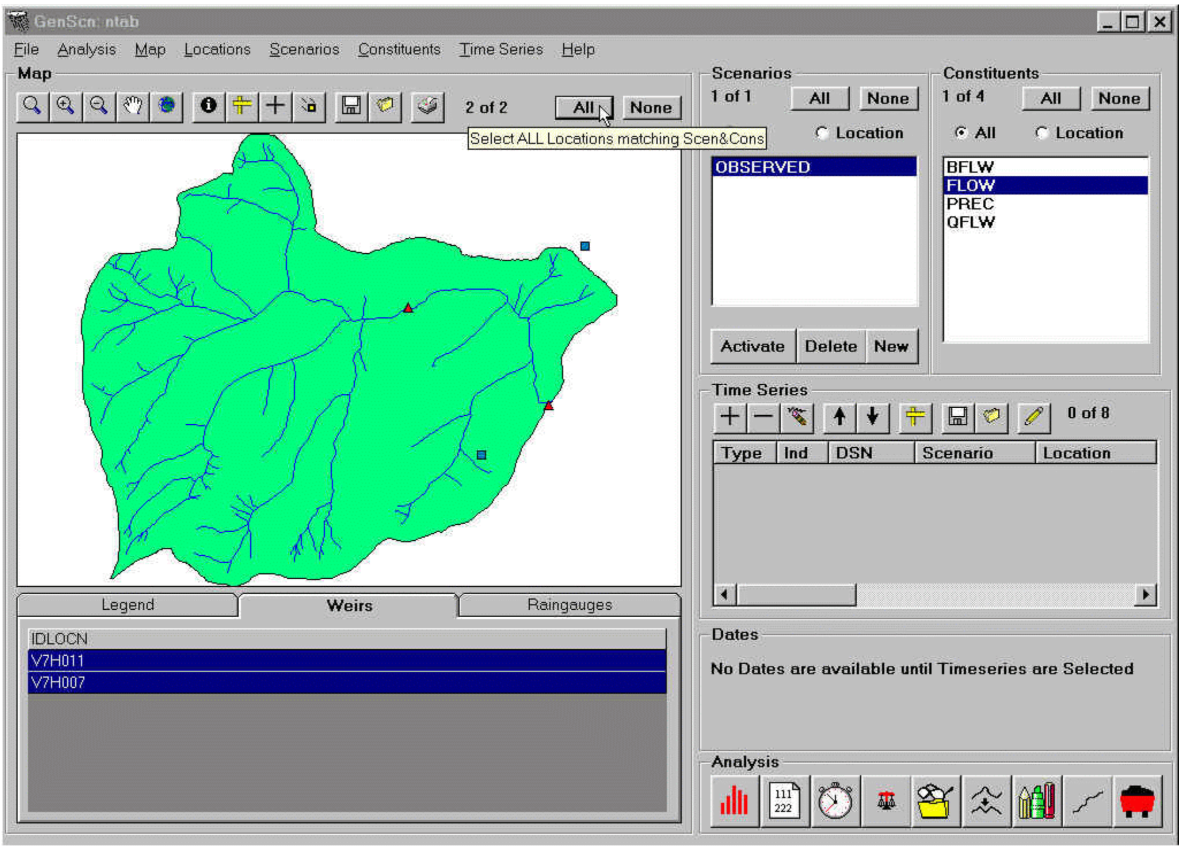


Select 'ntab.sta'.

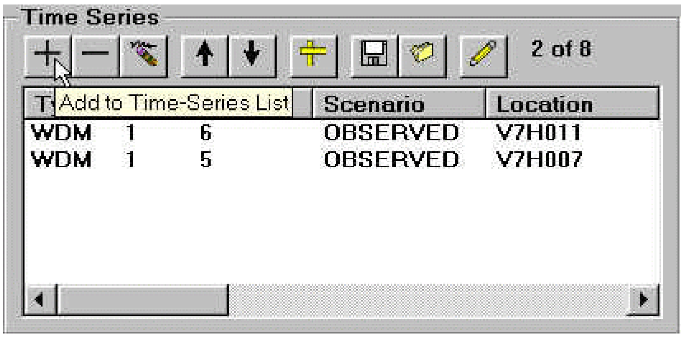


The Ntabamhlope example is now opened.

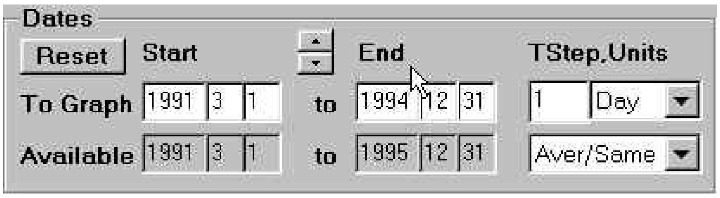
The observed flow can be viewed, for example, by selecting ‘Observed’ ‘Flow’ from the Scenarios and Constituents and the sites by selecting the ‘Weirs’ tab and ‘All’ on the map.



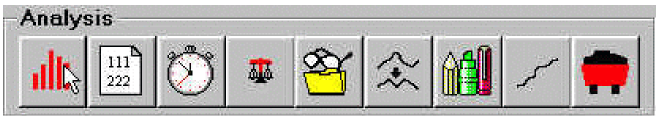
The selected weirs are then highlighted in red on the map and the time series data can be extracted from the 'WDM' file as follows.



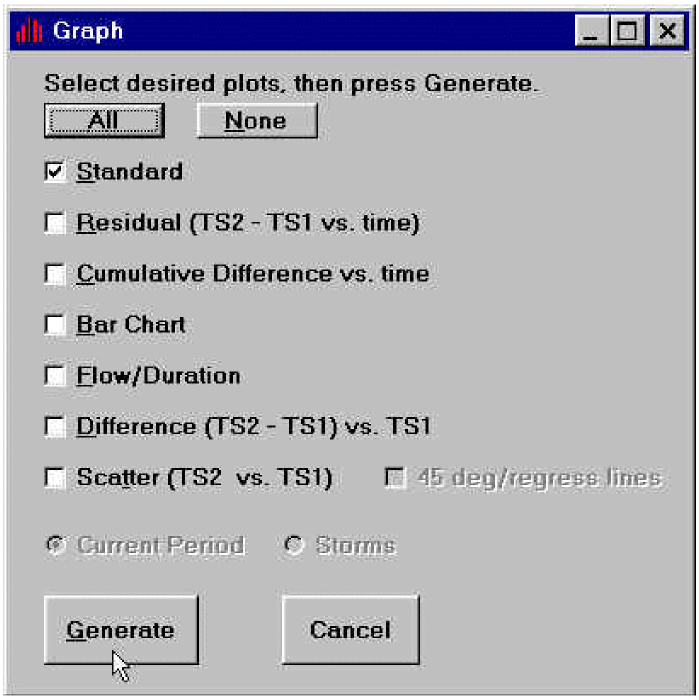
The time resolution can be varied.



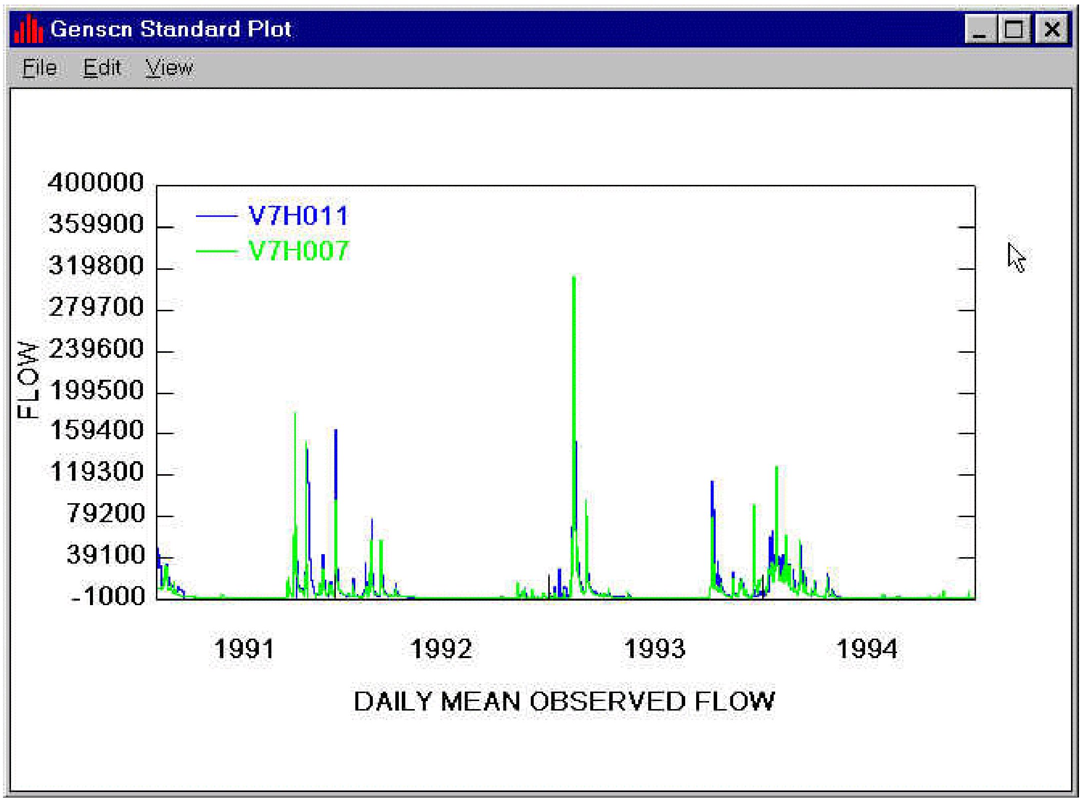
Then choose the graphing tool from the 'Analysis' toolbar.



Graphing options.

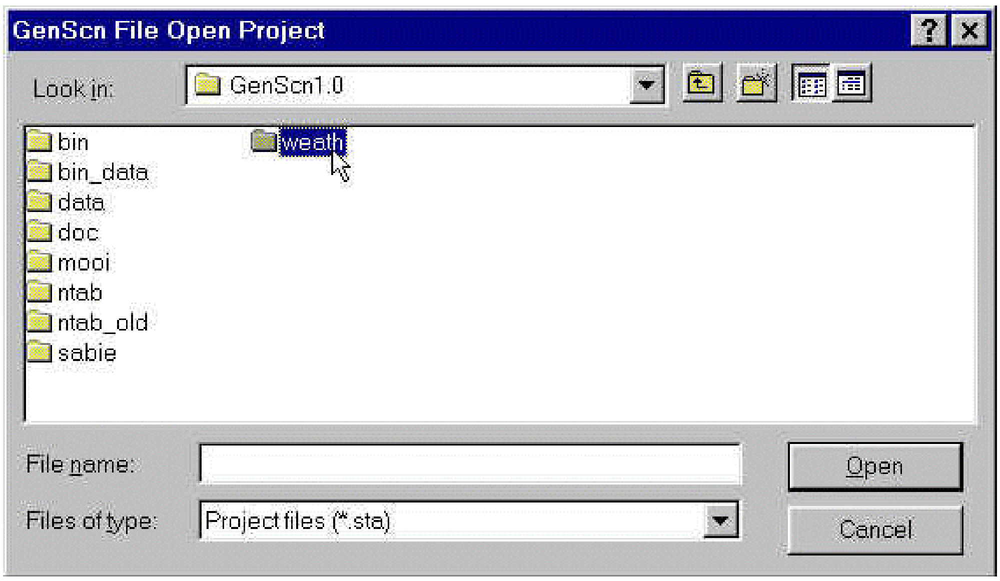


The graphs of the selected sites data are now displayed. The graph properties can be modified if required.

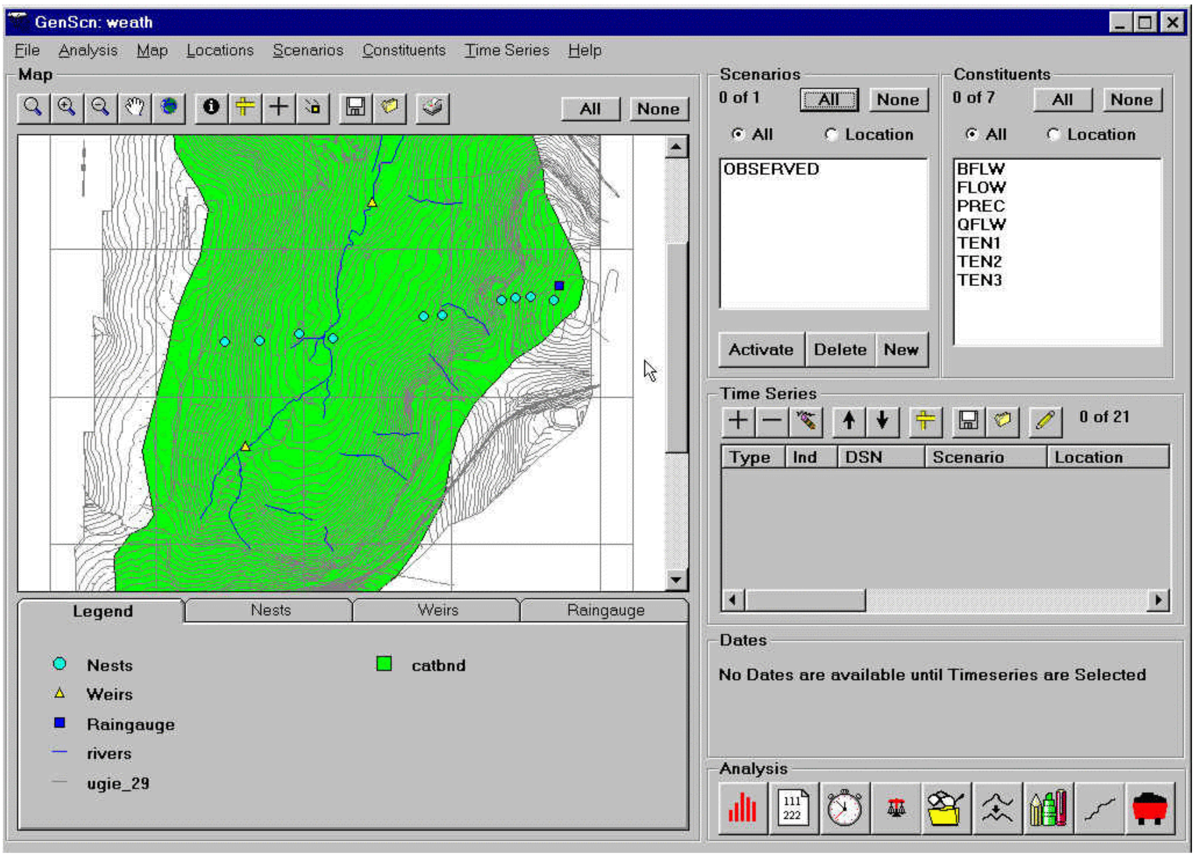


Opening the Weatherly example.

To open the Weatherly example, first close the ‘ntab.apr’ project then in the same way that the Ntabamhlope example was opened open ‘weath.apr’ from ‘C:\wrdapp\GenScn1.0\weath\’ directory.



The Weatherly example.



Due to real time processing constraints there are two time series entries for the precipitation at the Weatherly raingauge. Breakpoint rainfall at 1 minute intervals for use when comparing rainfall with 12 minute tensiometer data and 24 hour rainfall for the comparison of rainfall and runoff.

A more comprehensive USGS manual 'genscnpdf.pdf' for the operation of GenScn can be found on the CD in the 'Genscn' folder, in Acrobat format.