Institute of Hydrology

Natural Environment Research Council

A study of Dambo Hydrology in Southern Africa

Inception Report

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Executive Summary

This report is submitted as a discussion document. It investigates the options available for research into the hydrology of dambos in southern Africa. The reasons why this is considered to be an important area of work are discussed, and the outstanding scientific issues to be resolved in this field of research are identified.

Several options for the direction the study could take are put forward. The implications of each of these options for the modelling and fieldwork strategies that would need to be adopted, are examined. Three model types, commonly used in the simulation of hydrological processes are discussed: physically-based, conceptual and physical conceptual (or pragmatic physical models). The data requirements of each model type are specified.

The costs of each study option are discussed. Consideration is given to research already being undertaken and proposed for the future (both at IH and elsewhere) by others in this and closely related scientific fields.

Finally, a preferred option is selected. It is suggested that the use of hydrochemistry to investigate hydrological pathways represents (within the context of dambo hydrological research) a innovative way forward that would supplement the work presently being undertaken by others. It is felt that the potential for obtaining data from more than one catchment provides the opportunity for greater generalisation of results than would be the case if the fieldwork was concentrated at a single location. Furthermore, of the options considered, it is felt to be the approach that is most likely to be successful within the scope and time-scale of a PhD study.

Contents

1. Introduction

The objective of this report is to consider the scientific issues of importance in the field of dambo research with the principal aim of drawing up a programme of future research. The research strategy to be developed has two primary objectives: firstly, to fulfil some of the recommendations of the DAMOCO conference held in Harare in 1992, and secondly, to satisfy MPM's research interests with the ultimate aim of him completing a PhD thesis. It is intended that the work should be done in collaboration with the Geology Department of the University of Zimbabwe. It has been agreed that MPM will register as a Research Associate at the University of Zimbabwe. The benefits and costs of a range of proposals are considered. This first draft is presented as a discussion document.

In the next section the background to the project and details of the scientific issues requiring resolution are described. Various options for research are proposed. In section 3 the modelling and consequent fieldwork requirements for each proposed research option are considered. The financial implications of each option are discussed in section 4. In section 5 related research being undertaken both at IH and elsewhere is described. A proposed timetable is given in section 6 and a summary and conclusion are presented in section 7.

2. Project Definition

In this section the background to the proposed project is described. A definition of a dambo is given and the important scientific issues to be resolved in this field of research are listed. Finally proposed options for research are described.

2.1 BACKGROUND

April 1992

The NERC Terrestrial and Freshwater Sciences Committee, Expert Review Group on wetlands published a review of wetland research (NERC, 1992). This made several recommendations including the following:

- priority should be given to the development of wetland hydrological field methods and measurements

- there should be continued support for the work on the hydrology of wetlands in catchments

June 1993

AB produced for IH a discussion document entitled "Wetland ecosystems research initiative" (Bullock, 1993). Among others, the following issues were identified as being ones where future research activities could valuably be concentrated:

- There is much fundamental work to be done on the theory of water movement and soil physics generally as applied to wetland systems.

- There is a need for more routine monitoring of simple climatic and hydrological variables, such as water table, and more emphasis on extreme event components of the water balance.

- There is a need to determine how wetlands function as a component of the drainage basin with respect to groundwater recharge, groundwater discharge, flood generation/attenuation, sediment/toxicant retention, nutrient retention, micro-climate stabilisation etc.

October 1993 to April 1994

MPM expressed an interest in undertaking some long-term research with the aim of gaining specialisation in a particular field of study and obtaining a PhD. MPM hoped that the study to be undertaken would involve fieldwork and a significant component of overseas travel. IH management encouraged, and agreed financial support for, MPM in this endeavour. After discussion it was decided that a suitable topic would be a study of the hydrology of dambos in southern Africa. AB agreed to be MPM's IH supervisor as this fitted in well with his own research interests. It was also agreed that MPM should apply to register at the University of Reading. In recent years several members of IH staff have obtained PhDs from the University of Reading and there is a semi-formal link between the University and IH. Consequently, this seemed an appropriate choice.

AB in conjunction with Richard Owen (Director of the Geology Department at the University of Zimbabwe) submitted a proposal entitled "The Dambo Process Integration Experiment", to NERC Terrestrial and Freshwater Sciences Directorate for Science Budget funding.

April 1994

In order to facilitate this work MPM transferred to the Flow Regimes and Environmental Management Section (AG's section). It was agreed that MPM would spend the majority of his time doing the PhD study, but would also make contributions to the completion of Commissioned Research projects when appropriate; in particular maintaining links with the Jersey Small Catchment Study. MPM's time is presently funded from Science Commission. Until October 1994, MPM continued with his commitments to FAKF's section.

July 1994

MPM in conjunction with AB, wrote a concept note to be considered for ODA Technology Development and Research Programme funding. However, it was decided that the issues raised within this note were more relevant to the ODA Environment Research Programme. Consequently, this application was not carried forward. However, a formal grant application that was submitted "Southern Africa Water Rights and Discharge Consents" does include the financing of a temporary member of staff to digitise river networks and wetland boundaries.

August 1994

MPM submitted an informal study outline to Professor Peter Gregory, head of the Soil Sciences Department at the University of Reading. MPM was subsequently offered a place within the Soil Sciences Department.

MPM in conjunction with AB and Richard Owen submitted a concept note entitled "Management of Soil and Water Resources in Headwater Catchments in Southern Africa" to ODA Environment Research Programme and was subsequently informed (Hipwood, M., personal communication) that it would be considered by the Strategy Advisory Committee, for funding from this source.

September 1994

MPM and AB made a short visit to Zimbabwe. The main objective of this visit was to investigate the possibility of setting up a research programme in Zimbabwe and to discuss the options for research with relevant people in the country. This visit was very successful and a lot of information (much of which has been incorporated in this document) was gained. The idea of developing a research programme that would build on the work being done by others was well received.

October 1994

MPM registered for a higher degree by research within the Soil Science Department at the University of Reading, under the supervision of Dr. Lester Simmonds. MPM's fees were paid by IH.

November 1994

During the merit review procedure of Institute Science Budget proposals the Science Budget bid submitted by AB and Richard Owen was awarded an $\alpha3$ grade. It was noted that this was "a good proposal with a strong international dimension and was worthy of funding". However, this does not guarantee that funding will be made available for the project.

2.2 DAMBO DEFINITION

A dambo is defined as a "grassy depression, periodically inundated and at the headwater of a drainage system in a region of dry forest or bush vegetation" (Ackermann, 1936). Dambos show considerable variation in physical attributes, but are widespread in central and southern Africa, occupying about 10% of the total land surface. Many dambos retain extensive wet regions during the dry season. It is the availability of water, in otherwise dry areas or during dry periods, that make dambos a valuable resource.

Three spatial zones can usually be identified within a natural dambo catchment (Figure 1):

- the interfluve (upland), dominated by miombo forest of varying density
- the upper dambo, grassland seepage zone that is permanently wet
- the lower dambo, grassland that is wet during the rainy season (October to April) but dries out by the end of the dry season (May to September)

2.3 DAMBO UTILISATION

Within the SADC region, the current population of about 84 million is growing at a rate of approximately 3% per annum. Many people in the region have experienced a decline or stagnation in living standards since 1980. Significant increases in food agricultural productivity will be required to improve food security and the quality of life (World Bank, 1994).

Prior to European colonization the use of dambos for the cultivation of crops was a long established indigenous land-use practice enabling year-round crop production, since gardens could be hand-irrigated in the dry season from shallow wells excavated at their margins. In the early 1900s European farmers were quick to exploit the 'turf-like' soils in dambos because they were easily ploughed and the high moisture retention allowed cropping in the dry winter months. However, European agricultural practices (e.g. the introduction of drainage ditches) resulted in accelerated gullying of dambos on commercial farms, and the belief that all cultivation of dambos was *bad* became widespread.

In order to protect the widely perceived role of dambos in regulating downstream flows some colonial governments introduced legislation in the 1950s (e.g. Zimbabwe - Water Law, 1953) curtailing dambo cultivation, even in indigenous farming areas. As a direct result of this legislation, progressively greater areas of the interfluves were deforested and taken over for dryland cultivation. Crop production is now predominantly rain-fed, and consequently local populations are at risk from poor wet seasons. However, there is increasing pressure from local populations to utilise dambos for horticulture. Indeed in recent years, and particularly following the 1991/92 drought in southern Africa, the cultivation of dambos increased significantly in Zimbabwe, although it is still strictly illegal.

Recent scientific research suggests that, in some regions, the role of dambos on dry season flow regulation may be less than was previously suspected and they may even decrease dry season flow (Bullock, 1992). Other research has suggested that, within limits, agriculture on some dambos might be possible without detriment of the downstream flow regime (Faulkner & Lambert, 1991). Clearly the potential benefits to be gained from agriculture must be weighed against the harmful impact they might have on the natural environment. Within Zimbabwe the Research Council has made dambo agriculture a priority for future investigation, and the Health Authority is strongly supportive of dambo agriculture in order to relieve problems of malnutrition in parts of the country (Owen, 1994, personal communication).

2.4 SCIENTIFIC ISSUES

At present, the hydrological processes occurring within dambos are not fully understood, and the potential for sustainable use of dambo water resources is not clear. Some of the scientific issues to be resolved in this field of study are listed below:

- Recognising the variability amongst dambos that inhibits generalisation is it possible to develop a hydrological classification system for dambos, based on climate, geology, vegetation and internal attributes?

- Recognising that dambos are attributed a significant role in the hydrological cycle, what are the physical mechanisms governing the natural hydrological regime and water pathways of different dambo types and their importance in contributing to downstream river flows?

- Recognisng that horticulture should be promoted only if there is no significant detriment of downstream flows, what are the significant factors affecting evapotranspiration?

- Recognising the move towards sustainable production, what influences the sustainability (or otherwise) of both the dryland and wetland areas of dambos under natural conditions and different agricultural practices?

- Recognising the move towards sustainable production, what are the physical mechanisms controlling the processes of gullying and dambo degradation?

- Recognising hydrology as one component, what socio-economic, political and institutional factors must be taken into account when considering the use of dambos for agriculture?

An increased understanding of the processes occurring within a dambo catchment is important when considering the use of dambos for agricultural purposes. It is essential to know how the mechanisms of evapotranspiration and hydrological routing operate in a natural dambo environment, particularly in the region of the seepage zone at the dambo/interfluve boundary. Only by gaining an understanding of the natural processes can the impact of changes in land-use, both upslope and within the dambo itself, be predicted. It is also necessary to determine the extent to which dambos influence downstream river flows. One of the recommendations of the DAMOCO conference held in Harare in September 1992 was that research activities should be targeted at increasing understanding of dambo function and processes through the instrumentation of catchments (Bullock, 1994, personal communication).

2.5 STUDY METHODOLOGY - THE OPTIONS

Dambos can be considered 'receiving sites' or interruptions to water flow, between the interfluve (upland) slopes and the stream channels below. Their form, function and maintenance are governed by the soil and hydrological processes on the upland slopes, as well as processes within the wetland itself. Patterns of downstream flow emanating from dambos are regulated by the complex interaction of these influences. Consequently, it is necessary to gain an understanding of the important hydrological processes occurring in all regions of dambo catchments.

Throughout the literature there is a great deal of speculation about the hydrological processes and mechanisms occurring within dambo catchments (Ingram, 1991). Many hypotheses are reported with some supporting evidence, but as yet remain to be proved beyond doubt. With increasing pressure to use dambos for agriculture, it is essential to develop a greater understanding of dambo catchment dynamics in order to predict the impact of change caused by human activities.

Four options for the methodology of the research study are considered:

Option 1: *Development of a hydrological classification system for different dambo types*

It is a widely held perception that dambos vary both in their form and in the influence that they have on the hydrology of a catchment. The factors affecting differences may be both geomorphological and/or climatological. In this option, a study investigating differences within dambo catchments with the aim of deriving a system of dambo classification is proposed.

Dambo boundaries have been delimited in plan form on maps of Malawi, Zambia and Zimbabwe. These would be used in conjunction with available geological, climate and vegetation data sets to construct a dambo classification scheme. This would involve pulling together many different facets of dambo hydrology. It would be necessary to collate data, (probably in ARC/INFO) from a wide range of different sources and covering a range of factors influencing the role the dambo plays in catchment hydrology (i.e. climate, vegetation, soils, geology, land use and geomorphology). Some data are already available at IH from the FRIEND project, but additional data could be obtained from various sources including Departments of Water Affairs, Meteorological Departments and possibly Universities etc. for a number of catchments under different climatic regimes in Malawi, Zambia, Zimbabwe and possibly Tanzania. It is envisaged that a very simple water balance model could be used to determine differences in catchment response and relate these differences to the type of dambo catchment.

Option 2: *A detailed fieldwork investigation to develop increased understanding of the hydrological processes occurring within a particular dambo catchment*

In this option a detailed process study is proposed. Water table levels and soil water contents and hydraulic potentials would be monitored in both the upland (miombo forest) and grassland regions of a representative dambo catchment in its natural state. The chemistry of the groundwater and the streamwater at the catchment outlet would be monitored regularly. These data would be analysed to determine temporal and spatial variation in soil moisture, to provide estimates of plant water-use, and to identify hydrological pathways. A physically-based distributed catchment model incorporating soil-moisture accounting would be developed to simulate hydrologically important processes. The model would be used to ascertain the relative importance of different areas within the catchment in contributing to downstream river flows and the mechanisms operating in maintaining the relatively high soil moisture content at the seepage boundary at the interface between the interfluve and dambo. The applicability of the model would be tested by simulation of the hydrology of the instrumented catchment.

Option 3: *Development of a management tool that can be used to assist in land-use management decision making*

In this option a combined fieldwork and modelling study incorporating facets of both the above is proposed. It is suggested that a management tool is developed that could be used to contribute to the development of land management plans. Conceivably such a model could be used to minimize any adverse impacts of proposed land-use change on either the seepage zone or on the quantity and timing of streamflow. Such a model need not be as detailed as that required to simulate the physical processes occurring within a dambo catchment. It is envisaged that such a model could be a relatively simple rainfall-runoff model, conceptual in nature and simulating soil moisture and runoff at key locations in the catchment. Fieldwork would be concentrated on determining the key aspects required for simulation of soil moisture in the seepage zone and in determining the influence of land-use within a dambo catchment on downstream flow. Hydrochemical data may provide a good way of testing hypotheses about flow pathways. It would be important that the model utilises only parameters that can be determined from easily measured physical characteristics (e.g. climatic data, vegetation type, canopy cover, soil depth etc.). The applicability of the model would be tested by simulation of: firstly, the hydrology (streamflow and soil moisture content) of the instrumented catchment and secondly, the hydrology of other dambo catchments in regions with differing climatic and physical characteristics.

Option 4: *A remote sensing study*

Satellite remote sensing using synthetic aperture radar (SAR) has the potential to monitor spatial and temporal changes in surface soil moisture provided the effects of vegetation and surface roughness are understood. Sensors operating at microwave frequencies have long been recognized as the most suitable for soil moisture studies as a result of the unique physical link between soil moisture and soil dielectric properties which directly effect microwave emittance and reflectance. The European Space Agency ERS-1 satellite SAR has been used to monitor temporal changes in surface soil moisture over a wide range of soil moisture and vegetation conditions in the UK and Niger (Blyth, 1994). The results of these studies were mixed. Seasonal variations in soil moisture in the semi-arid region of Niger appeared to have a much greater influence on the radar backscatter than those of vegetation. However, the results obtained on the clay soils in the UK were disappointing; even in short vegetation conditions, no obvious relationships between radar backscatter and surface soil moisture were evident.

It is surmised that this may in part be a consequence of the fact that clay soils swell and contract with changing soil moisture; air cavities reduce the apparent soil dielectric. There was some evidence that increased vegetation moisture reduced sensitivity to soil moisture.

ERS-1 SAR data is presently available for southern Africa. SAR is not affected by cloud cover. The data are made available free of charge to Ken Blyth at IH on request. Early next year ERS-2 will be launched. The repeat period of ERS-2 will be 35 days, but in the first year both ERS-1 and ERS-2 will be operated simultaneously. Consequently the period between overpasses may be less, although the exact time scale is not yet known. In this option it is suggested that the SAR data could be used to investigate spatial and temporal changes in surface soil moisture content within a representative dambo catchment. The SAR could be used to identify seepage and wet areas in dambos. The time series data obtained could be used to indicate changes in the extent of seepage at the dambo/interfluve boundary following rain. It is hoped that this would increase understanding of the processes involved and by comparison between different areas might also assist in the classification of different types of dambo. The SAR resolution is nominally rated at 12.5 m but is in reality closer to 25 m (Blyth, 1994 personal communication). As with option 2, it is felt that in order to gain the most understanding from the information obtained it would be necessary to use the data collected in conjunction with a fully distributed physically-based model.

3. Technical considerations

The technical requirements of each of the study options listed in section 2.5 are different. It is essential that any fieldwork conducted is targeted at obtaining the data requirements for the model to be applied. Consequently the nature of the modelling to be undertaken needs to be ascertained before the fieldwork is defined. In this section the nature of the modelling required to fulfil the objectives of each of the options listed in section 2.5 is discussed and the consequent implications for fieldwork described. Possible locations for fieldwork are proposed and the availability of existing data at these sites reported.

3.1 MODELLING - OPTIONS

At present the hydrological and hydrogeological function of dambos is far from clear. The results obtained from empirical work alone may depend on uncontrollable and possibly unrecognized variables. Only a comprehensive understanding of the complete system will ensure that the wrong conclusions, and unwarranted generalisations, are not derived from a small set of experimental findings. There are two principal reasons for attempting to develop a mathematical model to simulate the hydrological behaviour of dambo/interfluve systems:

- to increase understanding of the system and allow testing of existing hypotheses on the movement of water within the dambo/interfluve system.
- to enable predictions to be made of consequences arising from future changes that might occur within a 'dambo' catchment (e.g. changes in land-use)

A wide range of deterministic hydrological models have been developed over the last few decades. These vary in complexity from very simple, lumped parameter models to highly complex distributed models incorporating algorithms that are based on an understanding of the physics of hydrological processes. In this section the different modelling requirements for each of the options listed in section 2.5 are discussed.

3.1.1 Model selection criteria

The major requirement of any model used/developed is that the most important hydrological and hydrogeological mechanisms controlling the catchment response to precipitation are represented in a way that is consistent with the accuracy required and the data available. For the purposes of the proposed study it will, in the first instance, be necessary to make a subjective assessment of which are the dominant hydrological processes operating in the dambo/interfluve system. However, as the study progresses it is anticipated that the assumptions made will be refined.

There are five questions that must be borne in mind in consideration of the model to be used:

i) What degree of model complexity is required? (i.e. how much 'fine structure' is necessary, and to what extent does the model need to be a distributed model?)

ii) Which terms of the water balance expression is the model required to predict?

iii) What is the time interval of interest?

iv) What is the accuracy of prediction that is acceptable?

v) What data are available, or will need to be collected, in order that the model can be used?

The answers to these questions are different depending on the approach to be taken in the study.

3.1.2 Physically-based models

Physically-based models are always distributed and are based on our understanding of the physics of the hydrological processes which control catchment response. The descriptive equations for physically-based models are in general non-linear partial differential equations that cannot be solved analytically for cases of practical interest. Consequently solutions must be found using approximate numeric methods, a wide variety of which are available and all of which involve some form of discretisation of the space coordinates and time ordinate. Solutions are found for the points or nodes defined by the space-time discretisation.

The complexities of the hydrological system are such that the majority of model components ultimately rely on empirical relationships, such as Darcy's law for flow through a porous medium. All such laws may, however, be validated by experiment independently of the model itself. This implies that the parameters of these laws and hence the model are, in principle measurable in the field. In practice it is often necessary to undertake model parameter calibration to some extent.

Physically-based models are either finite difference or finite element models. Such models are commonly used for groundwater modelling and allow a large variation in parameters and physical characteristics (e.g. the saturated hydraulic conductivity of soil) from one node to another. They have the advantage of allowing spatial variation even within a zone and, by reducing the nodal spacing, increased detail can be obtained in regions of particular interest. Since distributed models incorporate directly the non-linearities of the descriptive equations, short time-steps may be necessary to maintain a stable solution at times of rapid change (e.g. during the first stages of infiltration into a dry soil).

Physically-based models are highly complex and require significant amounts of data for parameter definition. Invariably, even on research catchments, there are insufficient data and the user has to resort to interpolation between measurement points. Consequently, there is always the risk that application without detailed knowledge of physical characteristics may not give meaningful results. The major advantage of physically-based models over other models is the spatially distributed nature of their input data and the fact that parameter values are less dependent on both the model structure and the period of calibration.

Examples of these models are the Systeme Hydrologique Europeen (SHE) model (Bathurst, 1986) the Stanford Watershed Model (Crawford *et al*, 1966) and the Institute of Hydrology Distributed Model (IHDM, see Beven *et al.*, 1987).

3.1.3 Conceptual (lumped) models

To model the complete catchment hydrological system is impossible. A complete representation of the physical and biological processes governing water movement can never be obtained. Consequently all models, even physically-based models, are a simplification of reality. Simplification can be either in the representation of the physical structure or in the representation of the processes involved. The most common simplification made in hydrological modelling is lumping or spatial averaging. The implication is that simulation of the system and its response can be represented mathematically using only the dimensions of depth and time (Blackie and Eeles, 1980). The processes are conceived as storage elements (i.e. reservoirs) each with prescribed capacities and outflow relationships.

Since processes are simulated on the basis of a conceptual approximation, it is necessary to adjust or optimise parameters until the model output is an acceptable estimate of the observed aspects of interest. In order to do this it is necessary to have observed data against which to calibrate model parameter values. Furthermore, if the model is to be generally applicable and used to assess the impact of changes in land-use, it is necessary that as far as possible model parameters have a 'physical' interpretation.

In recent years a number of semi-distributed lumped models have been developed. In these, parameters are lumped within specific areas and each is simulated as a submodel. The submodels are then linked in a manner that is compatible to the catchment being modelled, in order to determine the combined affect. A simple model of this form is the 'distributed' version of HYRROM (Figure 2). Within this model the evapotranspiration processes of different vegetation types are modelled separately (model algorithms having been developed from process studies), but there is no allowance for lateral flow between the different soil stores (Eeles and Blackie, 1993). Other models of this sort are the variable time interval model (VTI, see Hughes and Sami, 1994), a kinematic modular rainfall-flow model (RAFLES, see Stephenson and Paling, 1992) and the Pitman model (see Pitman, 1973). These last three models have been used in southern Africa and are reviewed by Hughes (1993). It is essential for the current study that, if a conceptual model is used, there is a soil store.

The VTI model (Figure 3) is based on a modelling time step that changes to correspond more closely to the real rates at which hydrological processes operate. The time step varies from 5 minutes to 1 day and changes in the time interval are triggered automatically within the model by user defined rainfall thresholds. However, it is necessary to have observed raingauge data with a time resolution at least as high as the finest time interval (Hughes, 1993).

3.1.4 Physical conceptual models

Physical conceptual models can be considered to be pragmatic models incorporating aspects of both physically-based and conceptual model philosophies. Often semi-distributed in nature they are usually modular in form and may operate at different levels of sophistication depending on available input data. Examples are: i) the agrohydrological modelling system ACRU (see Shultze *et al.*, 1989) and ii) the Peatland Hydrologic Impact Model (PHIM, see Guertin *et al.*, 1987).

ACRU has been developed within the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg, specifically for use in southern Africa. It is a "multipurpose daily soil water budgeting modelling system developed as an aid to objective water resources related planning ... that can be used at a point or on lumped or on distributed (heterogeneous) catchments " (Shultze *et al.*, 1989).

ACRU is established around a daily multi-layer soil water budgeting model (Figure 4). It has been structured to be highly sensitive to the effects of land use changes on the soil water and runoff regimes. When being operated in distributed mode, ACRU makes use of a cell-type discretization to sub-divide the catchment; each cell is effectively a subcatchment. The cells are interlinked in such a way that outflow from upstream cells is directed into downstream cells.

Much of the required input data, for instance potential evaporation, interception losses, soil water retention constants, potential and actual evapotranspiration, leaf area index, peak discharge equations etc. may be estimated by various methods according to the level of input data at hand. The system also comes with a landuse database information system which contains month-by-month time series information on over 50 of the more common land-uses found in southern Africa. These data have been collated from practical applications of the model in research studies. As well as different crops the database contains default input values on natural vegetation such as grasses, **wetlands**, exotic tree species, indigenous forests and pastures.

Each of the two soil horizons within ACRU require the input of the volumetric water content at three limiting soil moisture conditions: saturation (matric potential = 0.0), field capacity (matric potential = -5 to -35 kPa) and permanent wilting point (matric potential = -1500 kPa). It is also necessary to input the depth of both the upper and the lower soil horizon. When the model is being used in distributed mode it is necessary to determine area-weighted averages of these constants for each of the defined sub-catchments within the catchment.

PHIM is in many ways similar to ACRU, although it has been developed to determine the effects of drainage, peat mining and timber harvesting on streamflow response, in the northern USA (Figure 5). It is a model that is as physically-based as possible, with input limited to climatic data (i.e. precipitation, maximum and minimum daily air temperature) and descriptive information (e.g. vegetation type, canopy cover, soil depth). It consists of three independent land-type submodels, natural peatland, mined peatland, and mineral soil upland, which are configured by the user to represent the integrated streamflow response of a catchment of interest.

Within each submodel, evapotranspiration is determined as a function of potential evapotranspiration and is dependent on the elevation of the water table, the vegetation type and whether or not it is the growing or the dormant season. Infiltration is assumed to be instantaneous in some instances (e.g. undisturbed peat) but is otherwise estimated from an empirically derived equation. Overland flow is simulated as a function of excess rainfall (or snowmelt) and available depression storage and takes into account field slope and roughness. Water stored in depression storage is evaporated at the potential rate. Shallow subsurface flow is determined by application of a Darcy approximation with flow governed by the hydraulic conductivity of the soil. Similarly, deeper saturated subsurface flow is calculated with a variation of the theoretical Dupuit equation for an unconfined aquifer and is also dependent on the hydraulic conductivity of the soil. Streamflow from the peat is derived from dimensionless routing functions that represent water table elevation versus cumulative detention storage, and discharge versus water table elevation for natural peatlands. These functions have been developed from the peat profile description and simultaneous observations of water table elevation and discharge (Guertin *et al.*, 1987). There is full interconnection between the different submodels with both surface and subsurface flows being transferred through the system.

There are of course significant differences between the hydrology of the peat bogs of northern America and that of the dambos of southern Africa. However, the nature and level of complexity of PHIM would seem to suit existing knowledge of dambo systems. Many of the mechanisms being simulated within the model could be modified or similar ones derived (for example routing functions linking water table elevation and discharge) from data that could relatively easily be obtained for a dambo catchment. Where this is not possible simpler (more conceptual) algorithms might have to be developed initially, but with a view to increasing the complexity if possible in the future. One advantage of dambos is that the complexities of snow hydrology need not be considered.

3.1.5 Modelling requirements for the different study options

In all the studies proposed it is suggested that the key elements of the hydrology to be simulated are the catchment outflow and soil moisture content. However, the time-scale of the modelling and the degree of accuracy required varies. If chemistry is to be used to assist in the determination of hydrological pathways (section 3.2.2) it may also be necessary to simulate certain chemical determinands.

Option 1: *Dambo hydrological classification*

For purposes of classification, the main interest would be in ascertaining the long-term integrated effect of "different" dambo types on downstream flows and their influence on soil moisture within headwater catchments. Consequently, of interest would be annual or perhaps seasonal variation in flow and soil moisture content. A relatively simple lumped water balance model would be sufficient for this purpose:

$$Q_{seasonal} = P_{seasonal} - AE_{seasonal} - \Delta S_{seasonal} - \Delta G_{seasonal}$$

where: Q = streamflow
P = precipitation
AE = actual evapotranspiration
ΔS = change in soil moisture storage
ΔG = change in groundwater storage

Long records (e.g. 20 years) of flow, soil moisture and meteorology would be required from a large number of dambo catchments in order to ascertain how factors such as soil type, topography and vegetation influence the evapotranspiration and the catchment response to rainfall. It is envisaged that the model would need to be able to simulate seasonal flow volumes and seasonal change in average catchment soil moisture content to within 5%.

Option 2: *Process study*

In order to attempt to gain a complete understanding of the hydrological processes occurring within a particularly dambo catchment a physical model of the sort described in section 2.1.2

would be necessary. The model would need to be able to represent the important processes that influence the hydrology, within the 3 spatial zones of a natural dambo/interfluve system (section 2.2). It is proposed that the model should operate on a daily time-step. However, as noted in section 3.1.2 stability criteria would influence the size of time-steps to some extent and at times of rapid change (e.g. during a rainfall event) it might be necessary to reduce the size of the time step to hours.

The processes that must be modelled within each zone are:

- Evapotranspiration, including interception losses, plant transpiration and evaporation from bare soil, all of which will change through the year, depending on season and plant growth cycles etc. Relatively complex models simulating as far as possible the physical and physiological processes that actually occur in the soil-plant-atmosphere system now exist (Wallace, 1994).

- Soil moisture storage and subsurface water movement, including infiltration, vertical seepage (percolation), and lateral (downslope) interflow in saturated and non-saturated conditions as well as movements in the level of the water-table. All will be affected by soil characteristics (e.g. saturated hydraulic conductivity) and the underlying geology.

- Overland flow which is dependent on the rainfall intensity, soil infiltration capacity (likely to be very different between the sandy soils of the interfluve and the clay soils of the dambo itself) and local topography and vegetation.

It is envisaged that to be useful the model would need to simulate catchment daily mean outflow to within 10% and soil moisture content at key locations within the catchment to within 10%. Figure 6 shows "good" results from IHDM for simulation of the depth to the soil saturated/unsaturated boundary.

Option 3: Development of a management tool

A simpler semi-distributed model of the sort described in section 3.1.3 or section 3.1.4 would be necessary for a management tool. As noted in section 3.1.2, the large data requirements of physically-based models are not generally available even on research catchments and would certainly not be available at many locations within southern Africa. Consequently the use of a complex physically-based model as a management tool is unrealistic.

As a minimum requirement the model would need to be able to simulate the catchment outflow and soil moisture content within the three zones identified in section 2.2. As far as possible the model would have to be developed in modular form, with each model algorithm (representing a particular process or mechanism) being simulated as a separate module. Wherever possible the same algorithms should be used by each sub-model, the only difference being in model parameters. If each of the model algorithms is simulated as a separate subroutine this would enable them to be altered relatively easily and allow increased complexity and "realism" to be incorporated if the data were available. It is important that the subroutines which make up the model have compatible levels of complexity, since in any system chain, its strength depends on the weakest link.

As with the physically-based model it is suggested that this model operates on a daily time step and should simulate both catchment daily mean flow and soil moisture content at key locations to within 10%.

Option 4: *Remote Sensing*

It is envisaged that remote sensing would provide information that would be useful in determining hydrological processes occurring within a dambo catchment. In order that the greatest advantage of these data, namely the spatial coverage, are utilised to the full, it is proposed that it should be used in conjunction with a distributed physically-based model. It is suggested that the model would simulate soil moisture and catchment outflow on a daily time-step (again with the proviso that model stability is maintained). The satellite data obtained would be used to assist with model performance validation and so would necessarily need to provide quantatitive as well as qualitative information. Consequently, obtaining ground-truth information (section 3.2.2) would be essential.

3.2 FIELDWORK - OPTIONS

The data requirements of the model to be used will govern the nature of the fieldwork to be undertaken. Consequently the amount of fieldwork to be undertaken will vary depending on which of the options (section 2.5) is chosen.

3.2.1 Suggested locations for fieldwork

Since it is impossible to isolate the processes occurring within the dambo/interfluve system an integrated approach, necessitating an instrumented catchment, is required. It is proposed that any fieldwork should be carried out in Zimbabwe. IH has both on-going and intended future research interests in Zimbabwe (section 5.1) which would be complemented by an investigation into dambo hydrology. A suitable location for an experimental campaign has been identified at the Grasslands Research Station (GRS) at Marondera. This research station and the neighbouring Horticultural Research Centre (HRC) are both establishments of the Department of Research and Specialist Services (DR&SS). Figure 7 is an aerial photograph of this area. The fact that there is existing environmental research programme at this location would make the logistics of conducting fieldwork easier. Furthermore, the existence of long-term flow and meteorological data would provide a very useful dataset against which to check the performance of hydrological models.

During the visit to Zimbabwe in September 1994, MPM and AB met with John Jackson the station director of HRC. HRC shares the same site as GRS, but has a greater interest in the sort of work that is being proposed. John Jackson agreed in principal with the idea of IH establishing a hydrological research programme based at this location. However, Ron Fenner, the Director of DR&SS, did not give formal approval for research at this station before he retired at the end of October 1994. Mr. Fenner did agree to the proposed project in principle (Fenner, 1994 personal communication) and it is hoped that his successor will be able to give formal approval in the near future.

The dambo catchment at GRS (located 80 km south-east of Harare in Zimbabwe) is a suitable location for a catchment study. The catchment is 3.52 km^2. There is a complex flow gauging structure (Figure 8) on the catchment outlet (18°10'S, 31°29'E) with a capacity of 59.6

m^3s^{-1}. The station is on a tributary of the Manyame and is identified as station C43. The station was opened on 14/09/55 and data are available from 1/10/55. Data are collected by the Hydrological Branch, Ministry of Energy Water Resources and Development, Zimbabwe. Daily mean flows and monthly instantaneous maximums have been obtained for the period 1/10/55 to 30/09/93.

Rainfall and other meteorological data are available from several locations in the vicinity of Marondera. The meteorological stations and periods of operation are listed in Table 1. Some data for these stations have been obtained from the Meteorological Department in Harare. However time limitations and the fact that the computerised records were destroyed by a lightning strike at the Meteorological Department in 1993 meant that not all the available data have yet been obtained. The meteorological data available are rainfall, wet and dry bulb temperature, relative humidity, wind speed and direction, sunshine hours and pan evaporation data. Average annual rainfall is about 800 mm.

In option 3b (section 3.2.2) it is suggested that the possibility of conducting some fieldwork (i.e. collection of samples for chemical analysis) at Chiredzi is investigated. A research catchment established by the Sustainable Agriculture section of IH (section 5.1.2) exists at this site. Although collection of flow data only commenced this year, a dense network of neutron probe access tubes, tensiometers and raingauges has been installed at this location. The rainfall at this site is a lot lower than at Marondera. There is some debate about whether or not the "wetland feature" within this catchment can strictly be defined as a dambo. From surveys of the local people it is clear that in the past there were pools large enough to catch fish in. However, the feature is now significantly eroded, with a much reduced water retention capability. It is surmised that this may be a consequence of bad land use practise in the past. A comparative study using data collected both at Marondera and Chiredzi could be worthwhile, although there are other catchments were similar comparisons would be equally valid.

3.2.2 Suggestions for experimental work

In this section various options for experimental work are considered.

Option 1: Dambo hydrological classification

This option would not require fieldwork to be undertaken. The requirement would be for high quality long time series datasets of climatological data, streamflows and soil moisture status for a number of catchments located in various countries in southern Africa. There would also be a need for data describing catchment topography, soils, geology and vegetation cover. Some of these data could be obtained from the African FRIEND database, but it is envisaged that additional data would have to be obtained from the relevant authorities in each country. Detailed datasets exist for research catchments at Grasslands (Zimbabwe), Luano (Zambia) and Ntamathlope (South Africa) and it is hoped that permission would be granted to use these data. It would be necessary to broaden the scope of the study to African "wetlands" in general rather than just dambos.

Option 2: Process Study

A considerable amount of fieldwork would be necessary for successful completion of this study. In order to provide the data required for a physically-based model large amounts of data would need to be collected frequently. The following list details data that would be necessary for successful completion of this study. These data are presently not available for a dambo catchment in Zimbabwe, but would complement the data collection exercise presently being carried out by IH at Chiredzi in the south of Zimbabwe, which has a much drier climate than that at Marondera (section 5.1.2).

a) Regular monitoring of soil moisture and the water-table

The objectives of the soil moisture and water table monitoring would be two-fold:

- to quantify the soil-moisture regime which develops beneath the various areas of the dambo catchment and thereby assist in the identification of hydrological pathways.
- to estimate plant water use either directly from the depletion of soil moisture during dry periods or indirectly using daily soil moisture accounting models i.e. a variation on the Penman equation with a soil moisture regulating function (Harding *et al.*, 1992).

Downslope transects of neutron probe access tubes, tensiometers and piezometers would enable fluctuations in soil moisture content, hydraulic potential and the water table in both the dambo and the interfluve region to be monitored. It is proposed that transects of 5 access tubes are put in at 3 locations, with tensiometer arrays located at 4 key sites within the catchment (Figure 9). These will enable soil moisture content and suction to be monitored at different depths. Through analysis of the data increased understanding of vertical and perhaps to a limited extent, lateral soil moisture movements would be obtained. Determining the position of the zero flux plane, would enable separation of the zone where water is draining from that where it is being abstracted by the vegetation. Particular emphasis would be placed on monitoring soil moisture conditions at the dambo/interfluve boundary where analysis of Landsat thermal infra-red data has indicated that catchment transpiration is greatest during the dry season (Stewart, 1989).

Measurement of soil moisture content using the neutron probe is time-consuming and it is proposed that weekly measurements would normally be adequate. However, more frequent measurements should be attempted during and immediately following periods of rainfall. The neutron probe would have to be calibrated and it is suggested that the most practical and reliable way of doing this is using the French neutron capture method (Hodnett, 1994, personal communication). Soil characteristics such as dry bulk density, soil particle size distribution and hydraulic conductivity for samples obtained from representative locations within the catchment would also provide useful information for modelling purposes.

Table 1 Available Meteorological data from Marondera

Station Name	Station Nos.	Location	Altitude	Period Of Record	Comments
Marondera Irrigation	UQ3889	18°11'S 31°28'E	1630	1/11/68 - still open	
Marondera Lysimeter	UQ4191	18°10'S 31°30'E	1650	1/9/50 - 31/1/71	
Marondera Windmill	UQ4091	18°11'S 31°29'E	1620	1/12/38 - 30/6/92	
Marondera Police	UQ4688	18°11'S 31°33'E	1660	1/7/00 - still open	Rainfall only
Marondera Railway	UQ4689	18°11'S 31°33'E	1666	1/7/10 - still open	Rainfall only Moved position (10-20 m) in 11/61

b) Water Chemistry Monitoring

It is proposed that monitoring of streamwater chemistry could provide useful information that would assist in the determination of hydrological pathways within dambo catchments. Chemical signals in small streams can provide extensive information on how water moves through a catchment (Robson and Neal, 1991).

One recently proposed hypothesis is that water contributing to dry season river flows originates predominantly as hillslope groundwater, flowing beneath the dambo through the saprolite (weathered rock). It is believed that only a minor (if any) contribution to base flow originates from dambo storage during the dry season. That there is a significant hydrological pathway beneath (and by-passing) the dambo is suggested by new explanations of gully formation. McFarlane and Whitlow (1990) surmise that dambo gullies are formed by the upward discharge of deep water breaching the dambo clay where it is thin. The theory developed is that water discharging from the interfluve towards the dambo is split into two by a clay wedge on the dambo margin (Figure 10). The water is directed into one of two pathways: i) a shallow water system which moves laterally downslope over the upper surface of the clay wedge and is discharged at the seepage zone and ii) a deeper circulation system which passes beneath the dambo. As a consequence of the hydraulic pressure the water forced beneath the dambo clay will attempt to discharge upwards through the dambo clay lid. Some of the water will succeed in breaking through, predominantly in the vicinity of the dambo margins, forming springs. That water which fails to discharge upward is diverted laterally downstream beneath the clay before eventually discharging to the river channel at some downstream location.

It is proposed that hydrochemistry is used as an indicator of water sources, where it moves and how fast it travels in order to verify/disprove this hypothesis. Since the chemistry of the granitic basement complex is well understood (McFarlane, 1992) it is believed that the chemical signature of water originating in the deep groundwater system will be significantly different to that originating from the near-surface soils on the hillslope. Water originating from the deep groundwater system is likely to be rich in bases (sodium, calcium, manganese and potassium) in comparison to that originating from shallow sources. Conversely the shallow water is likely to be richer in iron and silica (Figure 11). Thus when the flow is predominantly groundwater fed (i.e. as the dry season is approached) the stream water should, if the theory is correct, be rich in bases and low in iron and silica. However, the concentration of the bases will decline and iron may increase in concentration through the rainy season as the contribution from the dambo itself becomes more significant. Figure 12 is a depiction of what is likely to be observed if this theory is correct. It is proposed that these would provide a useful indicator of the source of streamwater. However, because the determinands are non-conservative (i.e. concentrations are changed by chemical reactions occurring within the catchment) they are not ideally suited for hydrograph separation and so may not provide useful information on changes occurring through a storm event.

To obtain quantitative information on hydrograph separation a chemically conservative characteristic that shows substantial variation between high and low flows and that reflects differences between two chemically distinct "endmembers" (i.e. an acidic 'soil' component and a 'deep' well buffered component) is required (Robson, 1993). Two characteristics that are often assumed to be conservative are stream Acid Neutralising Capacity (ANC) and chloride. The ^{18}O isotope is also conservative. Chloride concentration can be determined through standard hydrochemical techniques. ANC is defined as the difference between strong cations and the strong anions in solution and can be estimated from pH using a non-linear relationship calibrated on spot-sampled data (Robson, 1993). ^{18}O can only be determined through more complex isotopic analysis.

Modern technology allows the continuous (i.e. every 15 minutes) monitoring of some chemical parameters; notably streamwater pH and conductivity (EC). Consequently, these could be monitored continually at the catchment outlet. However, it is essential to recalibrates the sensor electrodes using buffered solutions regularly (e.g. weekly). Furthermore, sensors may drift and the data obtained may not be that good (Robson 1994, personal communication). It is therefore suggested that manual measurements of pH and EC are made daily through the wet season and spot samples for full hydrochemical analysis are collected manually every week from the stream. Samples would be collected in narrow knecked 500 ml high density poly-ethylene bottles to avoid contamination. If possible the samples would be refrigerated before chemical analysis.

The chemistry of water taken from observation wells and piezometers in both the interfluve and the dambo would also be determined monthly, as would the chemistry of soil water obtained from different depths in the soil at different locations in the catchment. It would also be necessary to obtain frequent (hourly) spot samples through at least three storm events in order to determine the rapid response processes of the catchment. For each sample a complete chemical analysis would be undertaken. It is suggested that concentrations of calcium, sodium, manganese, chloride, nitrate, ammonia, sulphate, silica, iron and aluminium would be obtained through standard hydrochemical analyses. Gran alkalinity, required for determination of ANC can also be determined using standard methods of titration. The stream at C43 is ephemeral and only flows for about 8 months of the year. Groundwater samples would be obtained from 5 boreholes/piezometers at different locations within the catchment. Soil moisture samples would be obtained using suction samplers located at 12 locations within the catchment. It is estimated that full chemical analysis would be required for a total of approximately 180 samples each year.

It is also proposed that for additional information isotopic analysis (^{18}O) should be conducted on 20 streamwater samples collected through the wet season.

In order to have soil moisture data against which to calibrate any model used it would be necessary to have at least one transect with a minimum of 5 access tubes in which to make soil moisture measurements. The collection of these data would also assist in the determination of soil field capacity. As noted above the neutron probe would have to be calibrated and the most practical and reliable way of doing this is using the French neutron capture method. Soil characteristics such as dry bulk density, soil particle size distribution and hydraulic conductivity for samples obtained from representative locations within the catchment would also provide useful information for modelling purposes.

c) Micro-meteorological data

It is proposed that an automatic weather station (AWS) would be installed on the dambo to provide background meteorological data and to obtain the data necessary for the computation of Penman (1963) potential evaporation.

The AWS consists of instrumentation mounted on cross-arms attached to an aluminium mast. Output from the sensors would be directed to a Campbell logger, where the data would be converted automatically to engineering units by calibration equations incorporated in a computer program. It is suggested that the AWS instrumentation would be set up to provide the following data:

At hourly intervals:

- average air temperature (wet and dry bulb, °C)
- average wind speed (ms^{-1})
- average wind direction (degrees)
- average solar radiation (Wm^{-2})
- average net radiation (Wm^{-2})
- total rainfall (mm)
- surface soil moisture data from a surface capacitance probe

At daily intervals:

- total solar radiation (MJm^{-2})
- total net radiation (MJm^{-2})
- average air temperature (wet and dry bulb, °C)
- average wind direction (degrees)
- total rainfall (mm)
- maximum air temperature (dry bulb °C) and the time at which it occurred
- minimum air temperature (dry bulb °C) and the time at which it occurred
- estimate of potential evaporation from the Penman equation (mmd^{-1})

There would be two or three free channels on the Campbell logger that could be used for other instrumentation. It would be necessary to download the Campbell logger at approximately weekly intervals.

d) Measurement of stream flow at the catchment outlet

Water level is recorded using a chart recorder at the DWA structure on the catchment outlet. DWA have derived a rating equation for the structure and this is used to convert levels to mean daily flows. For study options 1,3 and 4 it is believed these data are sufficient. However, if the chemical monitoring scheme described above is adopted it would be necessary to obtain continuous flow measurement at the C43 gauging structure. This would require permission from the Hydrological Branch for detailed digitisation of the stage charts for this station.

Option 3: Development of a management tool

While less data needs to be collected for this study than option 2, some data would be required in order to calibrate the model and give confidence that conceptualisation within the model was correct. It is proposed that the emphasis of the fieldwork could be directed in one of two directions. Either: i) the collection of soil moisture data through the installation of neutron probe access tubes and tensiometers in transects from the interfluve onto the dambo of a representative catchment (i.e. that at Marondera) or ii) the collection of hydrochemical data, possibly from a number of catchments. Hereafter these are referred to as options 3a and 3b respectively.

Within the project there would be scope for consideration of economic factors (e.g. cost-benefit analysis relating to agriculture and the environment) and possibly the use of crop production models.

Option 3a: It is suggested that collection of the following data would be necessary:

- soil moisture content, measured using the neutron probe in at least one transect from the interfluve, across the dambo (as described above)
- soil hydraulic potential determined from four tensiometer arrays (as described above)
- water table levels from piezometers in at least one transect from the interfluve and across the dambo (as described above)
- outflow data from the catchment (as described above)
- rainfall and meteorological data to determine potential evaporation (as described above)

Clearly this would require nearly as much effort in terms of time for installation of equipment and weekly monitoring, as the full blown process study, described above.

Option 3b: It is believed that hydrochemistry offers a unique method whereby a lot of information can be gained for a relatively low outlay in terms of equipment and time required to install equipment. It has been shown that because a model adequately predicts flow this cannot in itself be used as proof that the structure within the model is valid. Chemical data can be used in place of detailed hydrological data to test hypotheses about flow pathways (Robson and Neal, 1991). The application of hydrochemical methods described above have not been widely practised in dambo research to date.

It is suggested that if the first field season data collection at Marondera was successful it might be possible to extend data collection to other catchments in order to allow some degree of generalisation in understanding to be gained. For instance data could be collected from other dambos in the vicinity of Marondera or perhaps from the IH research catchment near Chiredzi (section 5.1.2). If data were collected from this catchment it would complement the existing work being conducted by the Sustainable Agrohydrology section at IH as well as that proposed by the Remote Sensing section at IH (section 5.1.4). However, the first priority would be to obtain "useful" information from the catchment at Grasslands.

In order to link the chemical data to changes in water table level and soil moisture water content it would be necessary to install one transect of piezometers and neutron probe access tubes in the Grasslands catchment. These would also provide data that would be useful in callabrating any model that is used.

Option 4: *Remote Sensing*

Fieldwork requirements for a SAR study would be:

- Surface Capacitance Insertion Probe (SCIP) soil moisture data obtained at regular intervals (weekly) in transects across the dambo and interfluve.

- Volumetric soil moisture measurements for calibration of SCIP. This would need to be done 3 or 4 times at several different locations on each soil type within the catchment and covering a range of soil moisture conditions.

- Measurement of vegetation physical characteristics (including canopy cover, height and spacing) at different times of year.

- Destructive sampling of vegetation to determine dry bulk density and moisture content. In the UK this was done weekly at the same time soil moisture measurements were made. It would not be practical to do this as frequently in Zimbabwe, but it would be necessary to do it a minimum of 4 times a year in different seasons.

- Measurements of soil roughness.

In order to determine the dry bulk density of vegetation it would be necessary to dry samples in an oven. There are ovens at Grasslands and it is believed that they would be made available for use in the proposed project (Jackson, personal communication).

3.2.3 Assistance with fieldwork - the case for a counterpart

Much of the fieldwork described above would be very labour intensive. Consequently if fieldwork is to be included as a significant part of the study (i.e. particularly options 2, 3a and 4) it will be necessary to have assistance from at least one technician. It is felt that not only would this benefit the project, but would also through the training provided assist Zimbabwe in increasing in human resource terms, its research capability.

In the past counterparts assisting on IH projects have been given the opportunity to complete MSc courses in the UK. Enquiries have been made at the British Council (BC) in Harare, regarding the possibility of funding a counterpart for an MSc study as part of the proposed dambo research project. The most appropriate option for funding is the BC Technical Cooperation Programme. However, it is a pre-requisite that the person is nominated by their employer. This matter was discussed with John Jackson the director of HRC, but he stated that unfortunately there is no-one at this station who could presently be spared for an MSc study. An alternative is that IH proposes that someone else within DR&SS (not presently based at Grasslands) is given the opportunity to assist on the project and apply for a BC scholarship. However, if this were not possible it would be necessary for the project to employ a Zimbabwe citizen to work as a technician, although with this latter option the opportunity to do an MSc would not be available.

4. Financial Considerations

It is recognised that the purpose of Science Commission is to seed projects of interest to IH. It is not intended for long-term support for projects and is not an ideal way to fully fund a project. However, if one of the applications for funding that have been made since April 1994 (section 2.1) were successful this would enable MPM to complete a PhD within the broader framework of the projects proposed. This would reduce the need for Science Commission to support MPM. However, MPM's work would then be more specifically directed by the detail defined within the project proposals. Appendix A contains copies of the concept notes and Science Budget bid that are presently being considered for funding.

Table 2 lists the approximate costs that would arise from each of the fieldwork experiments described in section 3.2 and reports to which of the options they would apply. Where the opportunity exists to rent equipment, the costs in comparison to that required to purchase the same item are noted in Table 2. Rental where appropriate would be through the IH instrument section and would mean that faulty equipment could be replaced relatively quickly.

The PhD should be completed by October 1977. It therefore covers two and a half financial years. Although there would be no fieldwork costs associated with proposed option 1, the need to visit relevant authorities in several countries would mean there is a need for a significant travel and subsistence budget; it has been estimated as seven flights in the two and a half years. It would also be necessary to employ on a casual basis an ASO for a period of about 6 months to digitise dambo boundaries. This has been costed in at the cash cost of £62 per day. Although this is included within the proposal subbmitted to the ODA Technology Development and Research programme, it is recognised that the time-scale of this funding might not suit this proposed study. Other map based data (e.g. geology, soils and vegetation information) are already available as ARC/INFO coverages.

The costs of employing a technician to assist with fieldwork have been included in the expenses of options 2, 3a and 4. In addition it was reported that security of equipment is a problem at Grasslands (in the past pieces of equipment have been stolen) and it has been suggested that it would be necessary to employ a night watchman to safeguard important pieces of equipment (e.g. an AWS) (Jackson, personal communication). This is an additional expense that has been costed in to options 2, 3a and 4.

The standard hydrochemical analysis of water samples collected from both the stream and the groundwater boreholes could be done in Zimbabwe either by the laboratories of DR&SS or the University of Zimbabwe. The costs of these analyses are compared with the costs for the same analyses conducted by the IH laboratories, in Table 2. Zimbabwe does not at present have the capability to do isotopic analyses and these would have to be done in the UK.

To conduct any research in Zimbabwe it is necessary to have a research permit and to work for periods of longer than 6 weeks it is also necessary to acquire a temporary employment permit. A research permit costs US$100 (i.e. £70 approximately) and there may be an additional charge for an employment permit. This is estimated at being £100 for the purposes of costings. In order to obtain a research permit, it has been proposed (Owen, 1994 personal communication) that MPM registers for Research Associate Status within the Geology Department at the University of Zimbabwe. This would make it easier to obtain a temporary work permit. However, if the proposed research involves consultation with a Government Ministry (e.g. DR&SS) it is first necessary to obtain "ministerial approval" from the

Ministry. As yet this has not been obtained from DR&SS (section 3.2.1).

The other costs relating to each project are given in Tables 3 to 7. These are the total costs to be incurred in the next two and a half financial years. There is no breakdown of annual costs. MPM's staff-time has been costed in at the cash cost. Twenty four days of AB's time (for supervision) have been costed in each year at cash cost. Where there is a requirement for input by other members of IH staff, this has been costed in at FEC rates.

For research conducted at Marondera it would be necessary to rent a house for the duration of the fieldwork period (i.e. 2 years in the case of options 2, 3a and 4 and for a minimum of about 8 months in the case of option 3b). Housing is short in Marondera, but it is likely that something could be found for approximately £85 a month (Jackson, personal communication). It would also be necessary to purchase or rent a vehicle in order to travel from Marondera to Grasslands (a distance of 13 km) and also for transporting equipment. An estimate of £3000 for purchases of a vehicle and £1000 for vehicle running costs is also included in Table 2. If there is just one field season spent at Marondera (i.e. a possibility in option 3b) it might be more economical to rent a vehicle. Some subsistence has been costed in to each option for those days when it would be necessary to stay in a hotel. In option 1 this is estimates as £1500 per three week trip. In options 2,3a,3b and 4, 50 days over the two and a half year period are estimated at £50/day.

If in option 3b the second field seaon was spent at the IH research catchment near Chiredzi (section 5.1.2), this would have the advantage that the project infrastructure is already in place at this location; there is accommodation and a vehicle already being used. Consequently, if the second field season was spent here there could be a significant reduction in costs. However, if the second field season is spent either at Marondera or at another location there would be additional costs incurred (i.e. in accommodation, transport and possibly additional equipment). To cover these possible costs £5000 has been added to the fieldwork component of this study.

Within option 3b the cost of five flights has been included. It is envisaged that the flights would be used to get to Zimbabwe for fieldwork missions and to allow attendance at an approporiate international conference if the oppurtunity for such a visit arose.

For options 2 to 4 it would be necessary to import varying amounts of equipment into Zimbabwe. For equipment brought in and taken out at a later date a "temporary import licence" is necessary. A requirement of a temporary import licence is that there is a guarantor (e.g. the British High Commission) to guarantee that the equipment is taken out of the country at the end of a specified period. If any equipment is to be left in Zimbabwe permanently (DR&SS would be keen for the AWS to be left, Jackson, personal communication) it should be obtained for the University of Zimbabwe, since the University is excused payment of import duties (Owen, personal communication). Consequently there is no inclusion of import duties in any of the option costs.

For each of the options a contigency to cover unforseen expenses has been included. This varies depending on the amount of fieldwork to be undertaken and the consequent likelihood of the need for instrument repair and replacement.

Tables 3 to 7 show that the lowest cost option for this study would be option 1. Option 3b is the next most expensive study. However, it is felt that option 3b more closely fulfills the study objectives (section 1).

Table 2 Fieldwork Costs

Experiment	Purpose	Method	Equipment Required	Cost (£)	Lowest Cost (£)	Study Options for which expense is required
Soil Moisture						
Soil moisture content	Quantify temporal and spatial variation in soil water content	Measurement with neutron probe at approximately weekly intervals (more frequently following rain) along downslope transects from the interfluve to the centre of the dambo	Neutron probe including ratescaler and battery charger.	6528 (1800/annum rental ∴2 yrs = 3600)	3600	2,3a,3b
			Access tube (12 x 2 m tubes).	500	500	2,3a,3b
			Installation equipment for access tubes (i.e. augers, jacks, steel guide tubes etc.).	1600 (rental - £200 from IH)	200	2,3a,3b
			Neutron capture method of probe calibration (20 samples @ £80 a time).	1600	1600	2,3a,3b
			Water barrel for standard count reference.	100	100	2,3a,3b
			Access tube stands (locally made - 12 @ £20 a time).	240	240	2,3a,3b
	Quantify temporal and spatial surface soil moisture content	Measurement with surface capacitance insertion probe (SCIP)	Surface capacitance insertion probe	Rental = 1000/annum (at present time these are not available for purchase)	1000	4
Soil Characteristics	Descriptive parameters needed for modelling	Dry bulk density	Volumetric corer	100	100	2,3a,3b,4
		Saturated hydraulic conductivity	Field (disc) permeater	1200	1200	2
		Soil particle size analysis	Chemicals and measuring cylinders	500	500	2
Soil hydraulic potential	Quantify movement of soil moisture (vertical and to some extent lateral movement)	Measurement using arrays of tensiometers positioned at 4 locations within the catchment	Tensiometers, tensiometer boards, clamps, tubing and mercury (£600 per tensiometer array)	2400	2400	2,3a
			Augers for installation	300	300	2,3a
Position of the water table	Temporal and spatial fluctuations in water-table level	Measure with a well dipper in piezometers or observation boreholes	Access tubes: 5x4 m tubes	125	125	2,3a, 3b
			Well dipper	200	200	2,3a,3b
			Augers for installation if not obtained for neutron probe access tube installation	200	200	3b
Miscellaneous	Archiving software for data collected using neutron probe and tensiometers		SWIPS (IH software)	1000	1000	2,3a

Table 2 Fieldwork Costs - cont

Experiment	Purpose	Method	Equipment Required	Cost (£)	Lowest Cost (£)	Study Options for which expense is required
Vegetation characteristics	Determine vegetation dry bulk density and moisture content	Destructive sampling	Descent scales Access to drying ovens	1200	1200	4
Water chemistry	Determine temporal changes in chemistry in order to identify water sources and likely hydrological pathways	Analysis of weekly spot samples (more frequent during storm events) and samples collected from piezometers/boreholes - 180 samples/year	Analysis of 360 samples (standard hydrochemistry)	1080 (cost in Zimbabwe) 18000 (IH laboratory)	1080	2,3b
			- pH/EC meter for field measurement	300	300	2,3b
			Isotopic analysis - would have to be done in the UK - 20 samples (£20 a sample)	400	400	2,3b
			Suction samples (240 £50 each)	1200	1200	2,3b
			Narrow trenched, High Density Poly-Ethylene bottles (500 ml), 200 @ £1 each.	200	200	2,3b
			15 ml McCartney bottles for samples for isotopic analysis, 30 @ £2 each	60	60	2,3b
Micro-Meteorology Automatic weather station data	Basic background meteorological data for time-series input to a dambo model (e.g. rainfall and P.E.)	Regular measurement of wet and dry bulb temperature, rainfall, net radiation, solar radiation, wind speed and wind direction etc.) - hourly and daily values	AWS with Campbell logger	4100 (3500/annum rental ∴2yrs = 7000)	4100	2,3a,4
Miscellaneous Requirements			Tool sets - screwdrivers, spanners, multi-meter chain wrenches, plastic bags etc.	2000	2000	2,3a,3b,4
			Vehicle in Zimbabwe (purchase)	3000	3000	2,3a,4
			Vehicle running costs	1000/annum	2000	2,3a,4
			Vehicle in Zimbabwe (rent) for one field mission, i.e. 6 months	4000	4000	3b

Table 3 Option 1 - Total expenses to be incurred

	Comment	Costs (£)
Fieldwork	none	0
Technician in Zimbabwe	not required	0
Night watchman to guard equipment	not required	0
Travel	7 airfares @ £1000 each	7000
Subsistence	£1500/3 week trip	10500
Research/Temporary Employment Permit	not required	0
ASO (£62/day)	6 months casual employment for digitising maps - 126 days	7812
MPMs staff time	500 days HSO (£93/day)	46500
ABs staff time for supervision	72 days SSO (£127/day)	9144
University registration fees for MPM	£1600 per annum for 2 years	3200
Contingency		2000
TOTAL		86156

Table 4 Option 2 - Total expenses to be incurred

	Comment	Costs (£)
Fieldwork	see Table 2 for breakdown	26145
Technician in Zimbabwe	2 years employment @ £3000/year	6000
Night watchman to guard equipment	2 years employment @ £1.50/night	1100
Travel	5 airfares @ £1000 each	5000
Subsistence	Accommodation in Marondera (£85/month) + 50 days subsistence @ £50/day	4540
Research/Temporary Employment Permit	Required by Zimbabwe law	170
Shipping Equipment to Zimbabwe	150 kg at £2/kg (there & back) + shipping fee (£200)	800
MPMs staff time	500 days HSO (£93/day)	46500
ABs staff time for supervision	72 days SSO (£127/day)	9144
Staff-time for member of IH staff to train MPM in use of a physically based model (e.g. IHDM - through Ann Calver)	5 days, SSO @ FEC rate (£306/day)	1530
University registration fees for MPM	£1600 per annum for 2 years	3200
Contingency	Unforeseen expenses	4000
TOTAL		108129

Table 5 Option 3a - Total expenses to be incurred

	Comment	Costs (£)
Fieldwork	see Table 2 for breakdown	21465
Technician in Zimbabwe	2 years employment @ £3000/year	6000
Night watchman to guard equipment	2 years employment @ £1.50/night	1100
Travel	5 airfares @ £1000 each	5000
Subsistence	Accommodation in Marondera (£85/month) + 50 days subsistence @ £50/day	4540
Research/Temporary Employment Permit	Required by Zimbabwe law	170
Shipping Equipment to Zimbabwe	75 kg at £2/kg (there & back) + shipping fee (£200)	500
MPMs staff time	500 days HSO (£93/day)	46500
ABs staff time for supervision	72 days SSO (£127/day)	9144
University registration fees for MPM	£1600 per annum for 2 years	3200
Contingency	Unforeseen expenses	3000
TOTAL		100619

Table 6 Option 3b - Total expenses to be incurred

	Comment	Costs (£)
Fieldwork	see Table 2 for breakdown + £5000 for second year of filedwork	20845
Technician in Zimbabwe	not required	0
Night watchman to guard equipment	not required	0
Travel	5 airfares @ £1000 each	5000
Subsistence	Accommodation in Marondera for 2 fieldwork missions (16 months @ £85/month) + 50days subsistence @ £50/day	3860
Research/Temporary Employment Permit	Required by Zimbabwe law	170
Shipping Equipment to Zimbabwe	75 kg at £2/kg (there & back) + shipping fee (£200)	500
MPMs staff time	500 days HSO (£93/day)	46500
ABs staff time for supervision	72 days SSO (£127/day)	9144
University registration fees for MPM	£1600 per annum for 2 years	3200
Contingency	Unforeseen expenses	2000
TOTAL		91219

Table 7 Option 4 - Total expenses to be incurred

	Comment	Costs
Fieldwork	see Table 2 for breakdown	17100
Technician in Zimbabwe	2 years employment @ £3000/year	6000
Night watchman to guard equipment	2 years employment @ £1.50/night	1100
Travel	5 airfares @ £1000 each	5000
Subsistence	Accommodation in Marondera (£85/month) + 50days subsistence @ £50/day	4540
Research/Temporary Employment Permit	Required by Zimbabwe law	170
Shipping Equipment to Zimbabwe	50 kg at £2/kg (there & back) + shipping fee (£200)	400
MPMs staff time (£90/day)	500 days HSO (£93/day)	46500
ABs staff time for supervision	72 days SSO (£127/day)	9144
Staff time of member of IH staff (e.g. Ken Blyth) to train MPM in analysis of SAR image	5 days at PSO, FEC rate (£383/day)	1915
University registration fee for MPM	£1600 per annum for 2 years	3200
Contingency	Unforeseen expenses	2000
TOTAL		97069

5. Related Research

In this section research projects presently being conducted that need to be considered when deciding on the final form the proposed study should take are described.

5.1 IH RESEARCH PROJECTS

5.1.1 Collector well and community garden programme

This study managed by the Sustainable Agrohydrology section at IH began in October 1992. The principal aim of this project is to determine the technical, economic, financial, institutional, social and environmental viability of small scale irrigation schemes using water from collector wells sited in south-east Zimbabwe. The intention is to identify ways of improving the operation of the schemes and identify a basis for replicating the schemes on a wider scale (Lovell *et al.*, 1994).

5.1.2 The effect of land management on groundwater recharge

This study also managed by the Sustainable Agrohydrology section at IH has the aims of quantifying groundwater recharge and identifying recharge mechanisms. The intention is to use these observations to evaluate the effects of current and improved land management on groundwater recharge (Butterworth, 1994). The work is being conducted on a dryland (i.e. low rainfall) catchment near Chiredzi in the south of Zimbabwe. This area has on average about 500 mm of rain a year.

To quantify the groundwater recharge three approaches have been instigated: water balance studies at a range of scales (catchment, sub-catchment and point scale), direct measurement from soil physics measurements and evaluation of the chloride balance. In conjunction with this study, BGS aim to estimate recharge by monitoring water table fluctuations and aquifer properties at wells and piezometers around the catchment (Butterworth, 1994).

A firm decision has yet to be made but it is probable that the ACRU model (section 3.1.4) will be used for purposes of simulation in this study.

5.1.3 Southern Africa FRIEND

IH in collaboration with the relevant authorities in each of the SADC countries aims to develop a common hydrological database for the region and to analyse these data within the context of water resources for sustainable development in a changing environment.

5.1.4 Proposed remote sensing activities in Zimbabwe

It is recognised that remote sensing has the potential to provide hydrological information about dambos from the local to the regional scale. JBS in conjunction with Andrew Sheppard (a PhD student, based at the University of Leiscter but jointly supervised by JBS) will use data from the Along Track Scanning Radiometer (ATSR) mounted on the European Space

Agency's satellites ERS-1 and ERS-2 to provide surface temperature measurements over an area of 500 x 500 km of eastern Zimbabwe. It is intended that by combining the satellite surface temperature with ground-based measurements of near surface temperature an estimate of the latent heat flux (the energy equivalent of evaporation) will be obtained. The ground-based surface temperature measurements will be made at two experimental sites, one near Marondera (probably at HRC) and one near Chiredzi (Stewart, 1994).

5.2 NON IH RESEARCH

5.2.1 SAREC Research Project

This project, is a collaborative study managed by the University of Zimbabwe and Lund University, Sweden. It consists of several different components with the principal aims of researching "the nature and the suitability of a number of different aquifer types in Zimbabwe for use as a water resource for subsistence irrigation" (SAREC, 1994). The work is concentrated on three locations - the HRC, Shangani and Chizengeni. There are five programmes of research being undertaken in the following fields:

- Hydrogeology - the objective of this study is to investigate the nature, origin and physical functioning of three shallow aquifers. The work undertaken includes: investigation of the geological nature of the aquifers; the material nature of the aquifers by physical and chemical analysis of the aquifer materials; determination of the hydraulic characteristics of the aquifers by measuring the hydraulic parameters (hydraulic conductivity, infiltration rates etc.) and the water resources by analysis of the hydrological parameters (precipitation, stream discharge and evapotranspiration).

- Geophysics - the scope of this programme is to use geophysical techniques (e.g. resistivity and seismic refraction surveys) for investigating shallow groundwater resources. The aims are to determine the geometric extent of aquifers in three dimensions; to identify hydrogeological zones within the aquifers; to correlate geophysical signatures with aquifer materials and hydrological and hydrochemical properties.

- Plant water use and soil moisture - production of horticultural crops on dambos at Marondera and in nearby communal areas is being investigated. This work is principally being conducted by Mr. Fabian Chigumira of DR&SS. The main aims are: to determine the effect of dambo cultivation for horticultural crop production on water use and to devise optimal water use strategies for horticultural crop production on dambos.

- Hydrochemistry - the scope of this study is to use isotopic and hydrochemical investigations to estimate the origin and average turnover time of groundwater. Investigations include the use of the radioactive isotope tritium, the stable isotopes deuterium and oxygen-18 and traditional hydrochemistry. However, monitoring is limited to groundwater samples collected on average every six months.

- Remote Sensing - this is planned for the future but the exact details of the work to be undertaken are yet to be decided. However, it is believed the emphasis will be on geological and structural mapping.

5.2.2 British Geological Survey: Sustainability of yield from wells and boreholes in hard-rock aquifers

This project is being conducted in the same catchment that the Sustainable Agriculture section of IH is working in south east Zimbabwe. The project is aimed at obtaining a better understanding of the groundwater resources of hard-rock aquifers and in particular the shallow weathered layer. The lack of sustainability of yield from wells and boreholes may be due to a decline in groundwater levels regionally and/or in the vicinity of the well. A long-term regional decline may result from a gradual reduction in recharge due to changes in land-use or climate or from a level of abstraction greater than the average annual recharge. A pronounced near-well decline in water-levels will occur in aquifers where the transmissivity is relatively low.

Detailed investigations are being conducted to identify which of the above factors are contributing to falling water-levels in the wells and to explain the spatial variability in well performance. A parallel programme is also underway at six other sites in the region to evaluate the comparative potential of boreholes, large-diameter wells and collector wells to provide a sustainable source of water. A series of pumping-tests carried out on each type of well are being analysed and the results used to model the long-term drawdown under different recharge scenarios.

5.2.3 Soil Science Department at the University of Zimbabwe

Mike McGowan in the Soil Science department at the University of Zimbabwe is investigating the effects of cultivation practices on soil water budgets. Tillage trials are being conducted at three dryland locations in Zimbabwe in order to ascertain the effect of different tilling practices on soil moisture (McGowan, 1994, personal communication).

Mike McGowan is also investigating the possibility of deriving soil water release curves from a single paired measurement of moisture content and suction (Williams and Ahuja, 1993). This work consists predominantly of laboratory experimentation and computer modelling (McGowan, 1994 personal communication).

5.2.4 DR&SS related research

Mr. Isiah Mharapara is presently conducting research at Marondera. The exact details of this work are unknown, but it is believed that the main emphasis is an investigation of horticultural production based on ridge and furrow methods. It is understood that at least part of this work involves the monitoring of piezometers placed across a small dambo at HRC, Marondera. This is a spur to the main dambo at this location and is downstream of the C43 gauging structure.

5.2.5 The Land and Water Management Project in Zambia

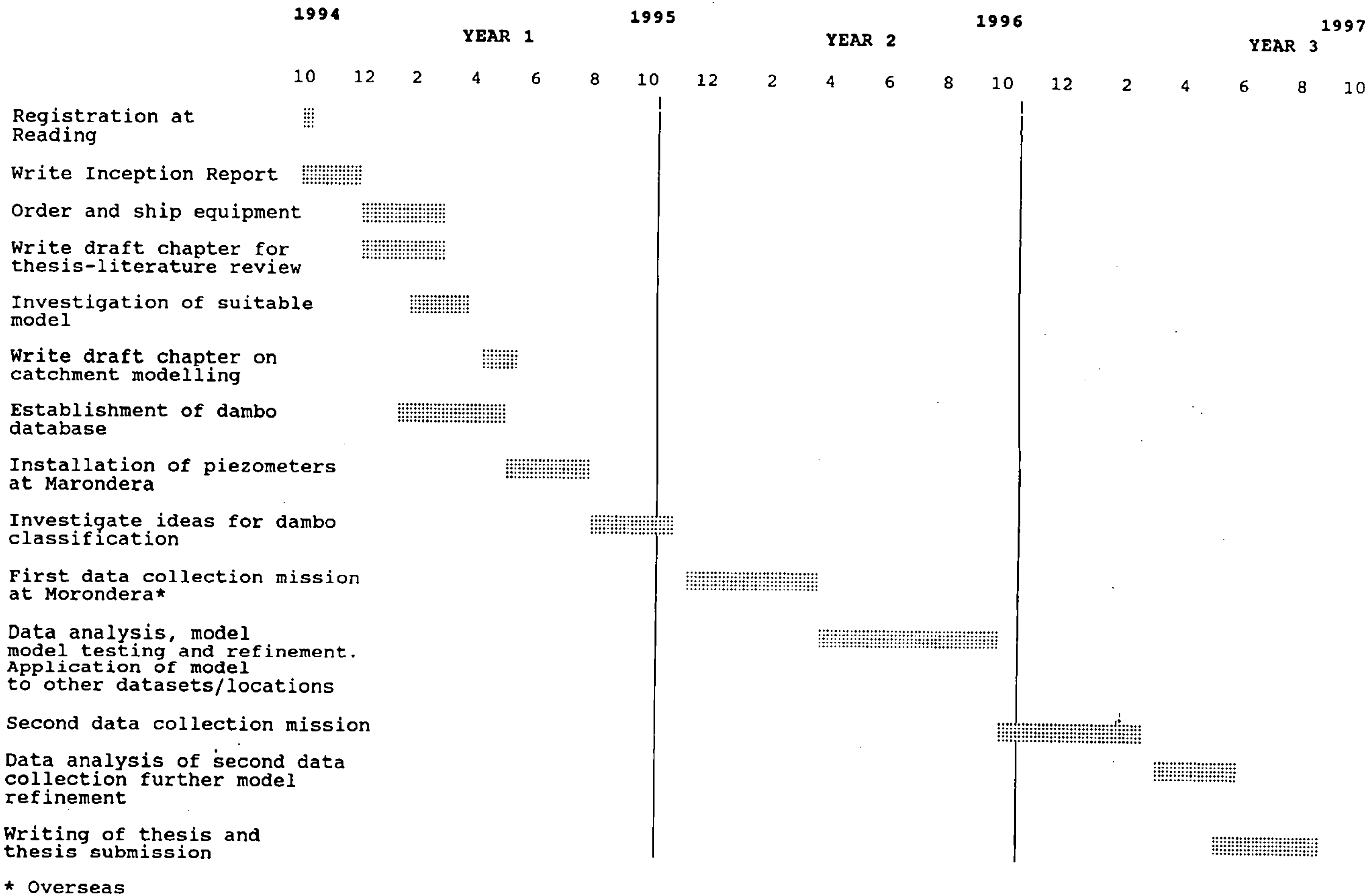
In Zambia the Land and Water Management Project (LHWP) is being run in Western Province. The objective of the project is the evaluation of the potential of the different wetland types for purposes of agriculture. The work is being carried out predominantly in the floodplain of the Zambezi River. A measurement programme commenced in 1989 involving the measurement of rainfall, water levels and discharges as well as "other characteristics" of wetlands (LWMP, 1994). This measurement programme is continuing. Water management trials have also been conducted at some locations within Western Province.

6. Timetable

If a PhD is to be obtained from this research project it should be completed within three years (i.e by the end of September 1997). It is therefore essential that if fieldwork is to be a component of the study it should commence as soon as possible. Furthermore, it will be a lot easier to install the majority of the equipment during the dry season than during the wet season. Consequently it is suggested that installation of equipment should begin at the latest by the end of April 1995. It takes 4 to 6 weeks to ship equipment from Europe to Zimbabwe and so the equipment needs to be purchased and despatched at the end of February 1995 at the latest.

Table 8 details the proposed timetable for project option 3b listed in section 2.5. It is envisaged that if one of the other fieldwork options (i.e. 2, 3a or 4) was to be instigated a similar timetable would be required.

Table Timetable for Option 3b



7. Summary

It is essential that the proposed study seeks to complement rather than duplicate the work that is presently being conducted in southern Africa (section 5), it must therefore be unique in some way. It is also essential that the work is of benefit to the countries of southern Africa and that emphasis should be on work that is generally applicable and not site specific. It is also vital that there are possibilities for continuation of the work once the PhD is completed.

The **preferred option is 3b**, the development of a management tool in conjunction with the use of hydrochemistry to gain an increased understanding of the hydrological pathways in the dambo system. Within the time-scale and scope of a PhD study it is felt that this option is the most likely to be successful; it is not dependent on the time consuming installation of a lot of equipment and much of the chemical analysis can be done for a reasonable cost in Zimbabwe. Furthermore there is less scope for problems with project management since there is no requirement to hire technicians and night watchman etc.

This option offers the opportunity to obtain data from a number of catchments, rather than just one and so is more amenable to generalisation of results. The use of detailed stream hydrochemistry to determine hydrological routing within dambo systems has not been attempted to date and the work would complement that already being undertaken by other researchers in this field. In particular it would seem to fit in well with the work presently being conducetd by the SAREC research group. If the study is conducted at both Marondera and Chiredzi this would supplement the work being undertaken by Sustainable Agrohydrology section in the land management study (section 5.1.2) as well as the remote sensing work proposed by Stewart (section 5.1.3).

While not ruling out the possibility of using other models it is proposed that the development of ACRU as a management tool for dambo catchments should be investigated first. This model has been developed specifically for use in southern Africa and is proposed for use by Butterworth in the IH land management study (section 5.1.2). It would therefore seem sensible to build on the development work already undertaken. It is also to be hoped that by using the same model as Butterworth there will be increased opportunity for generalisation of results.

In conclusion it is felt that option 3b fulfills the objectives outlined in the introduction (section 1). It is an innovative approach to the study of dambo hydrology and complements well the work already being undertaken.

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Figure 1 Schematic representation of the zones, usually identified in a Dambo catchment

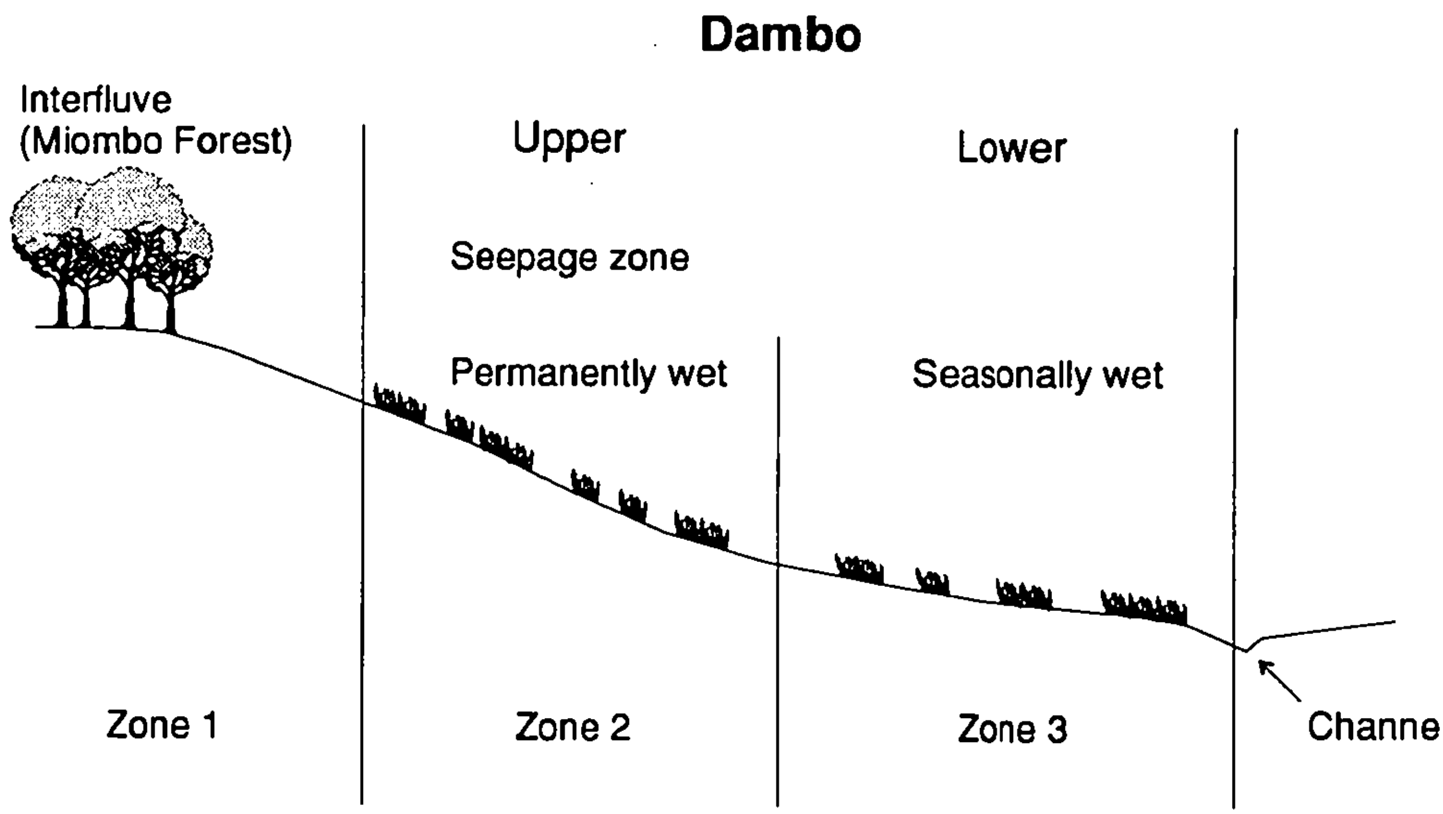


Figure 2 HYRROM Hydrological Model
(From Eeles and Blackie, 1993)

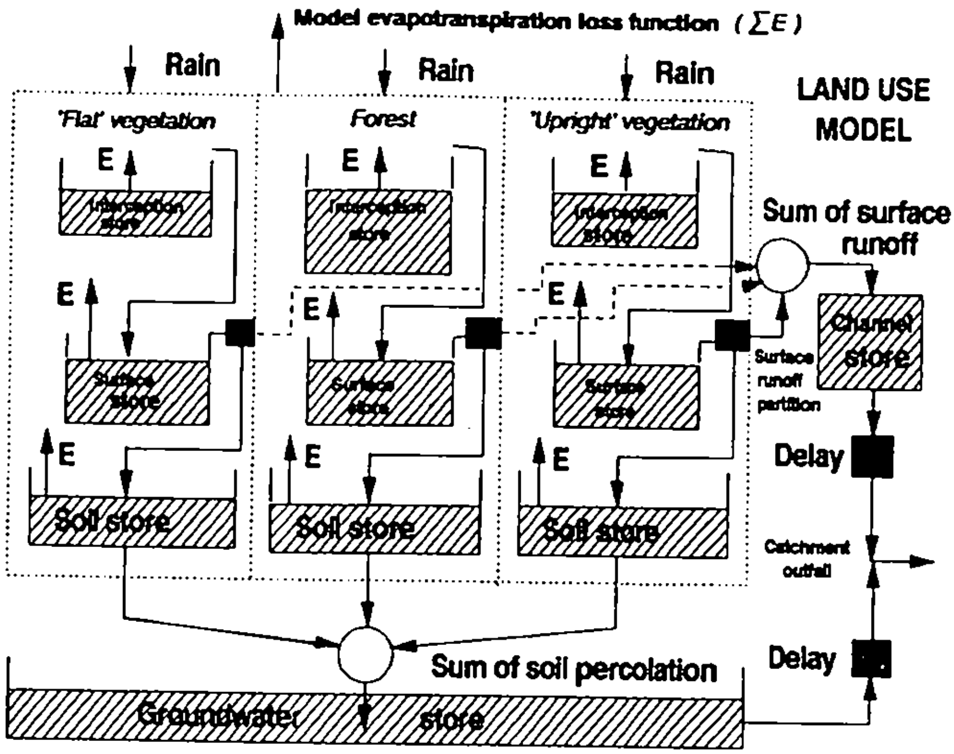


Fig. 1. Diagram of the land-use model, showing the model structure for the three types of land use, and the combination of inputs to the surface channel store and groundwater storage.

FIGURE 3: STRUCTURE OF THE VARIABLE TIME INTERVAL MODEL (AFTER HUGHES, 1994)

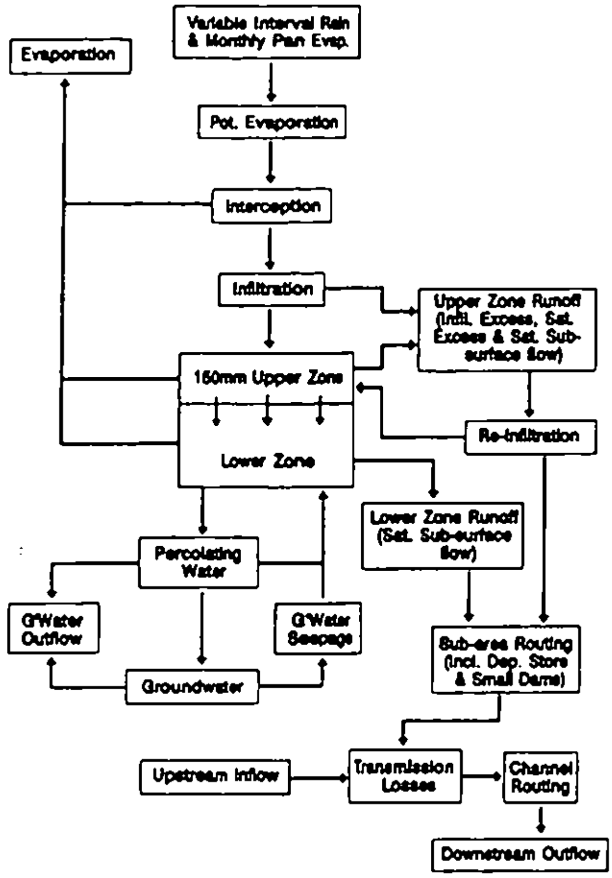


Fig. 1. Flow diagram to illustrate the operation of the variable time interval (VTI) model.

Figure 4: The ACRU Agrohydrological Model
(From Schulze et al, 1989)

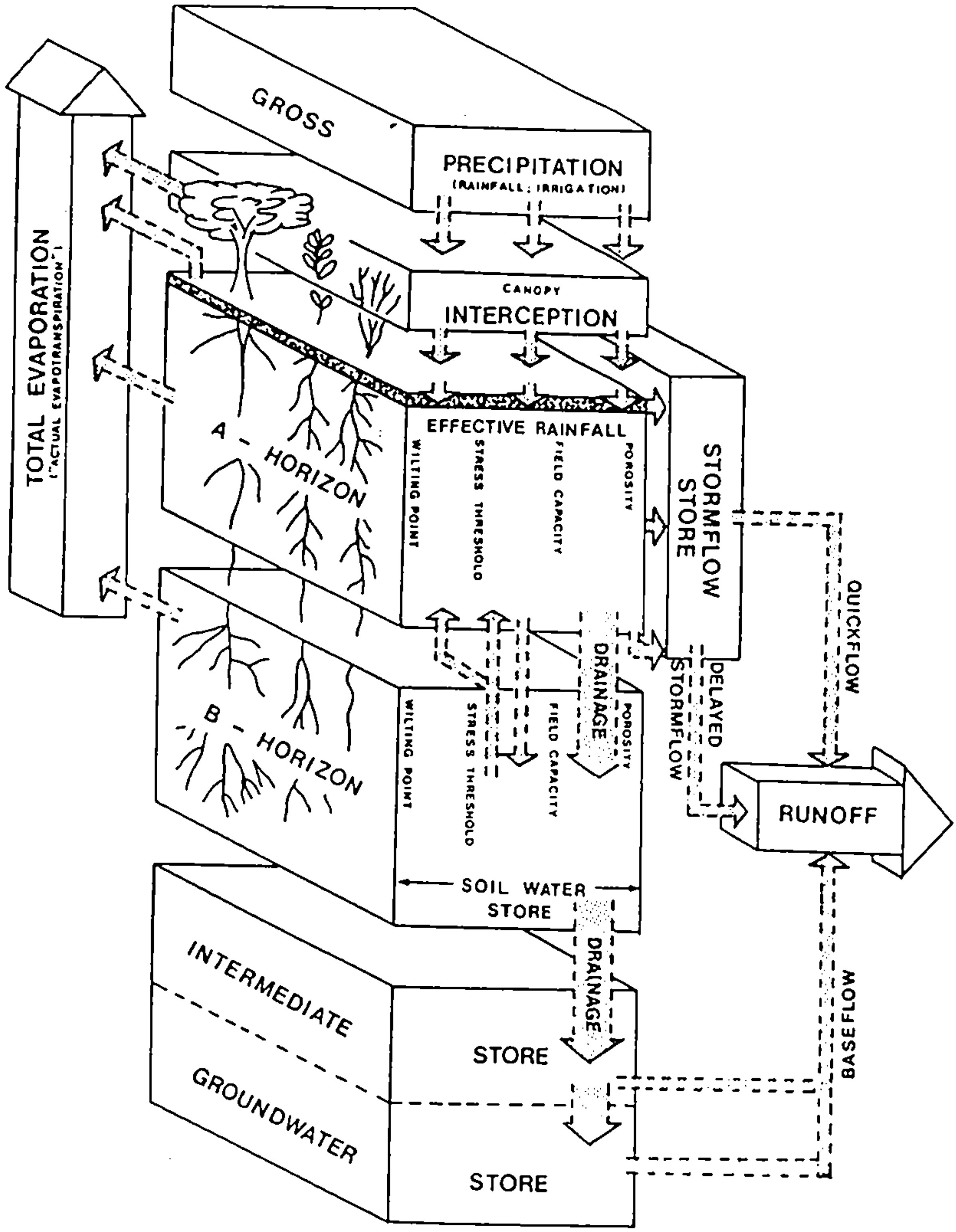


Figure B.2.2 The *ACRU* agrohydrological modelling system : General structure

Figure 5 PHIM Hydrological Model

(From Shiang-Yue Lu et al, 1993)

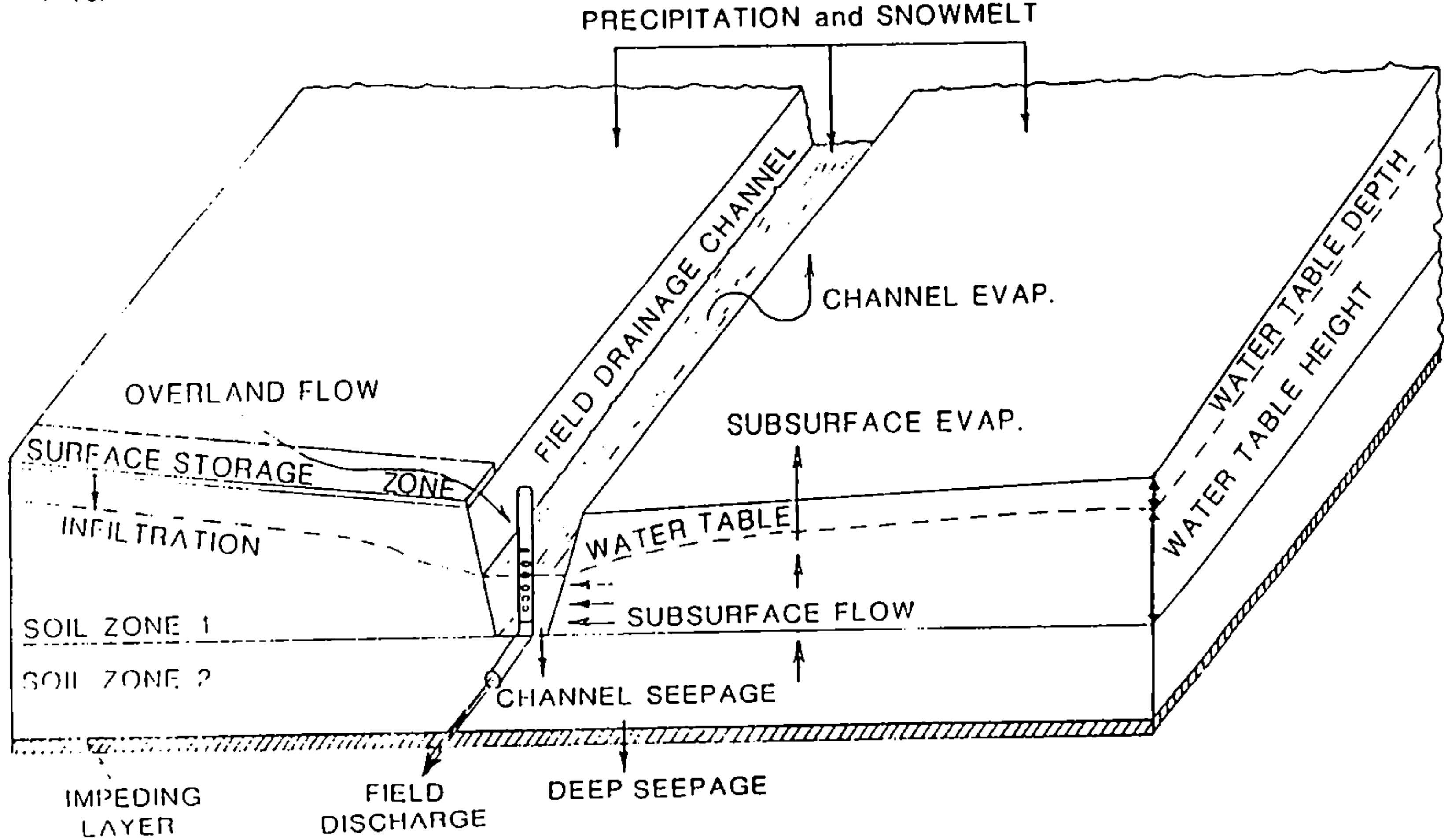
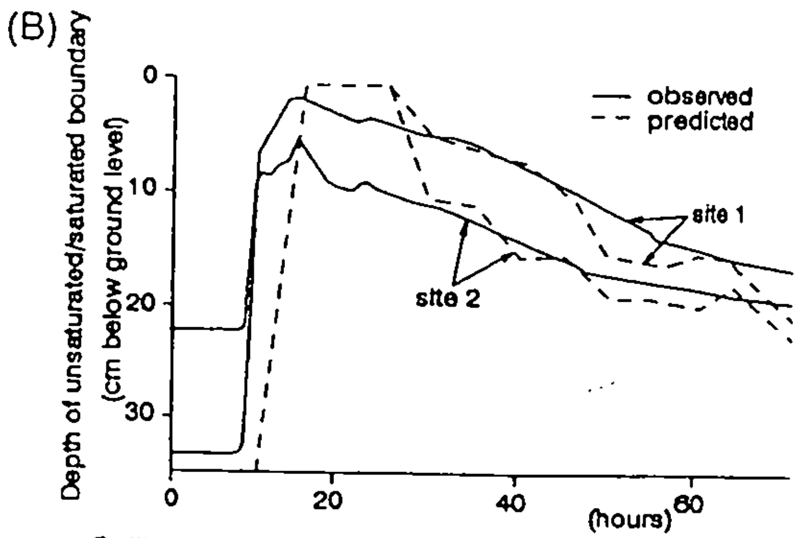


Fig. 14 Water budget for an average peat mined field.

Figure 6: IHDM Simulation Of Soil Moisture
(From Calver, 1993)

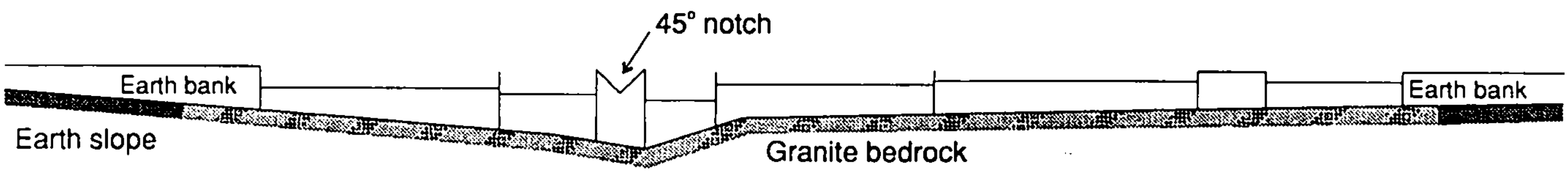


Calibration against soil saturated/unsaturated boundary (20-22/10/88); Larochette,Luxembourg.

Figure 7 Ariel View Of Grasslands, Marondera
The Dambo Of Interest Can Be Identified As The Darker Region In The Middle Of The Photo.

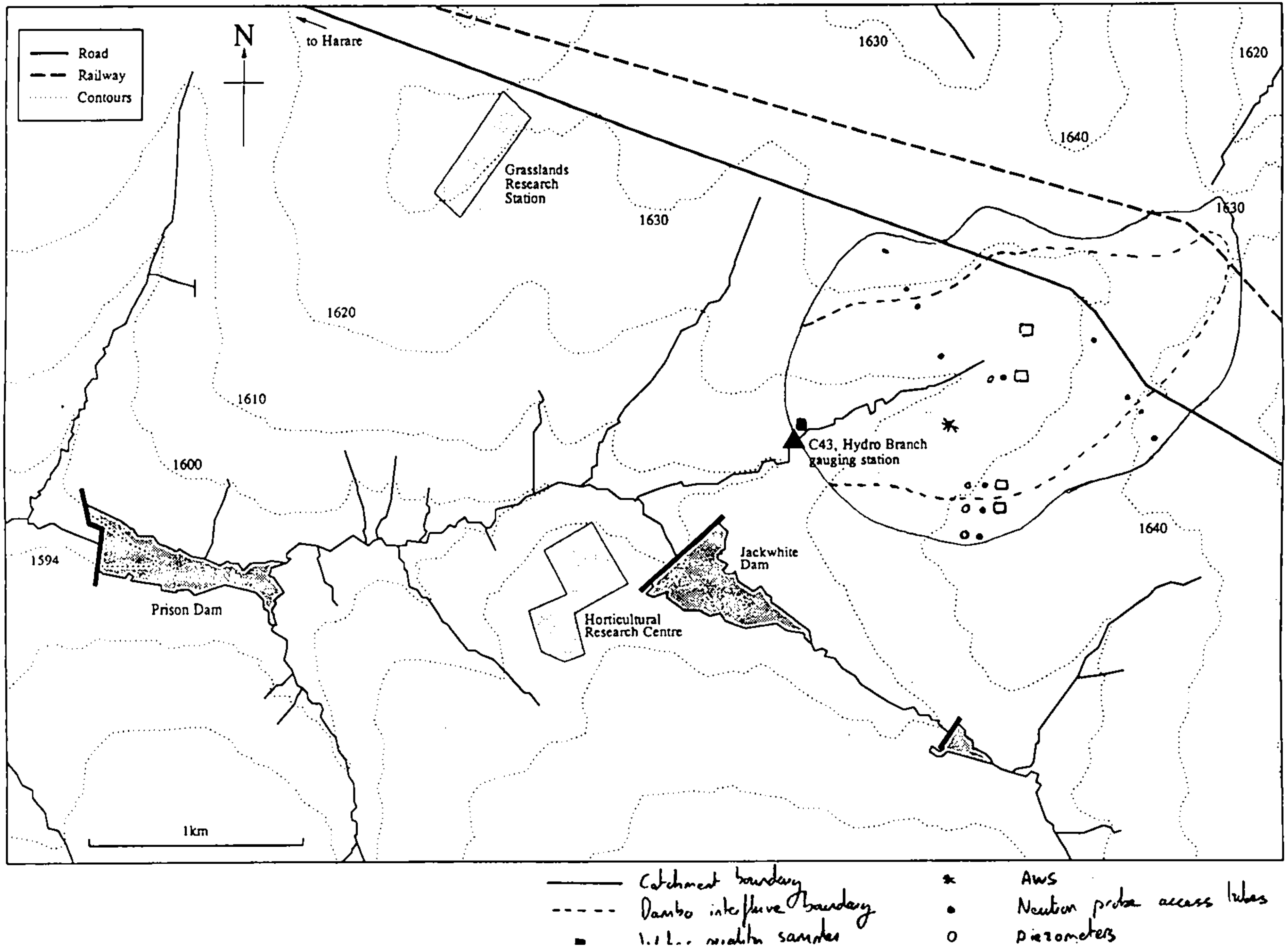
Location of gauging structure

Figure 8. Gauging weir, C43 at Marondera Grasslands
(Not to scale)



Note: Earth banks have been constructed with clay cores

FIGURE 9: PROPOSED INSTRUMENTATION TO BE INSTALLED FOR PROCESS STUDY - OPTION 2



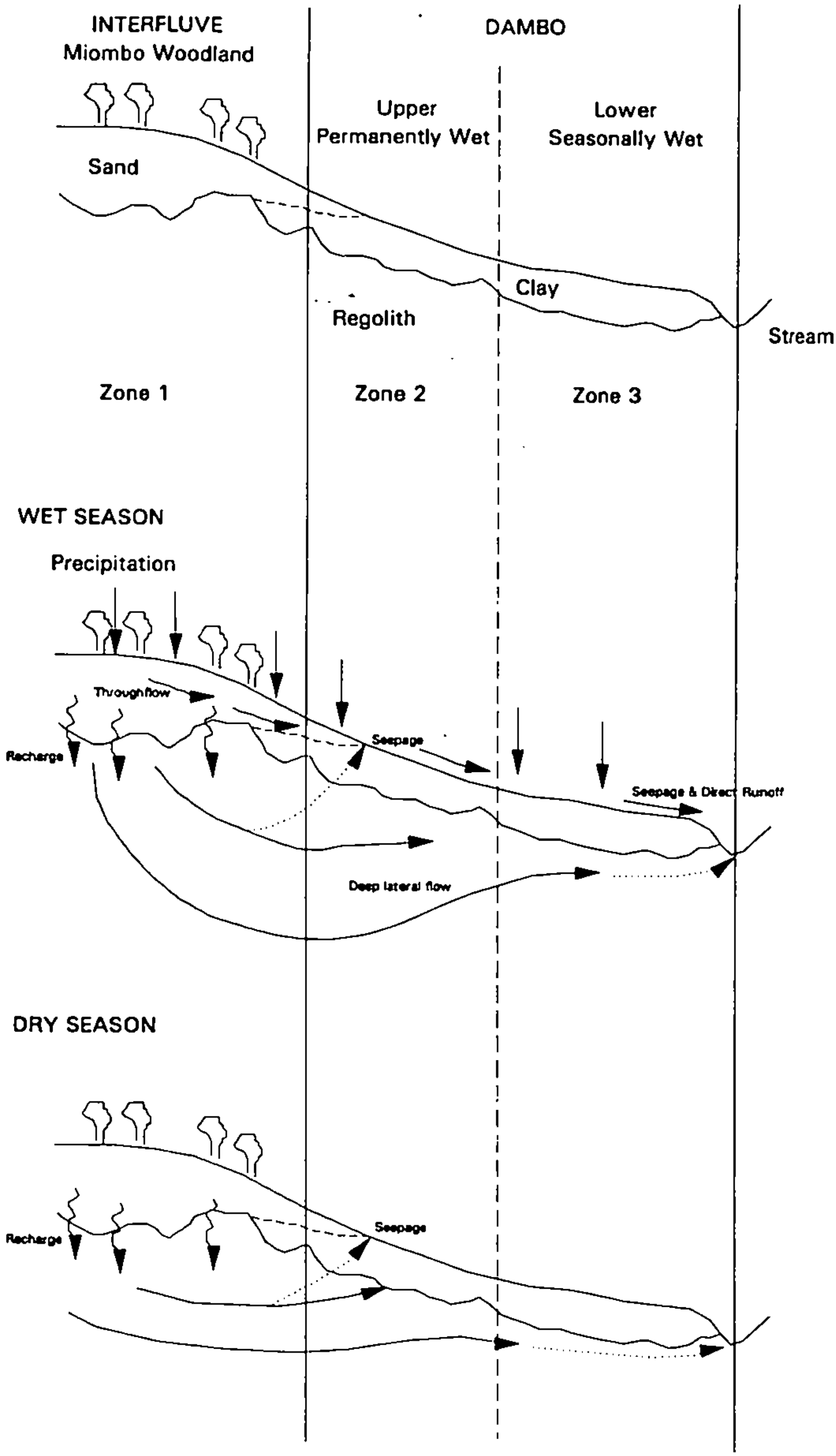


FIGURE 10 Schematic representation of a dambo and suggested hydrological pathways (after, McFarlane and Whitlow, 1990)

Figure 11: CHEMISTRY ASSOCIATED WITH DIFFERENT HYDROLOGICAL PATHWAYS
(FROM McFARLANE and WHITLOW, 1990)

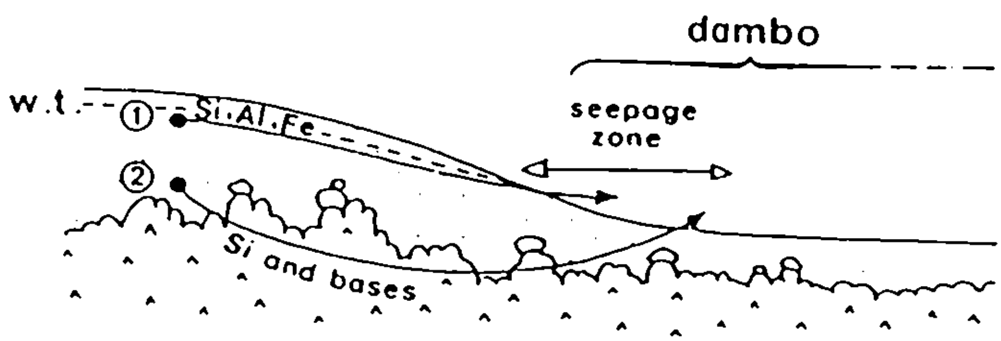
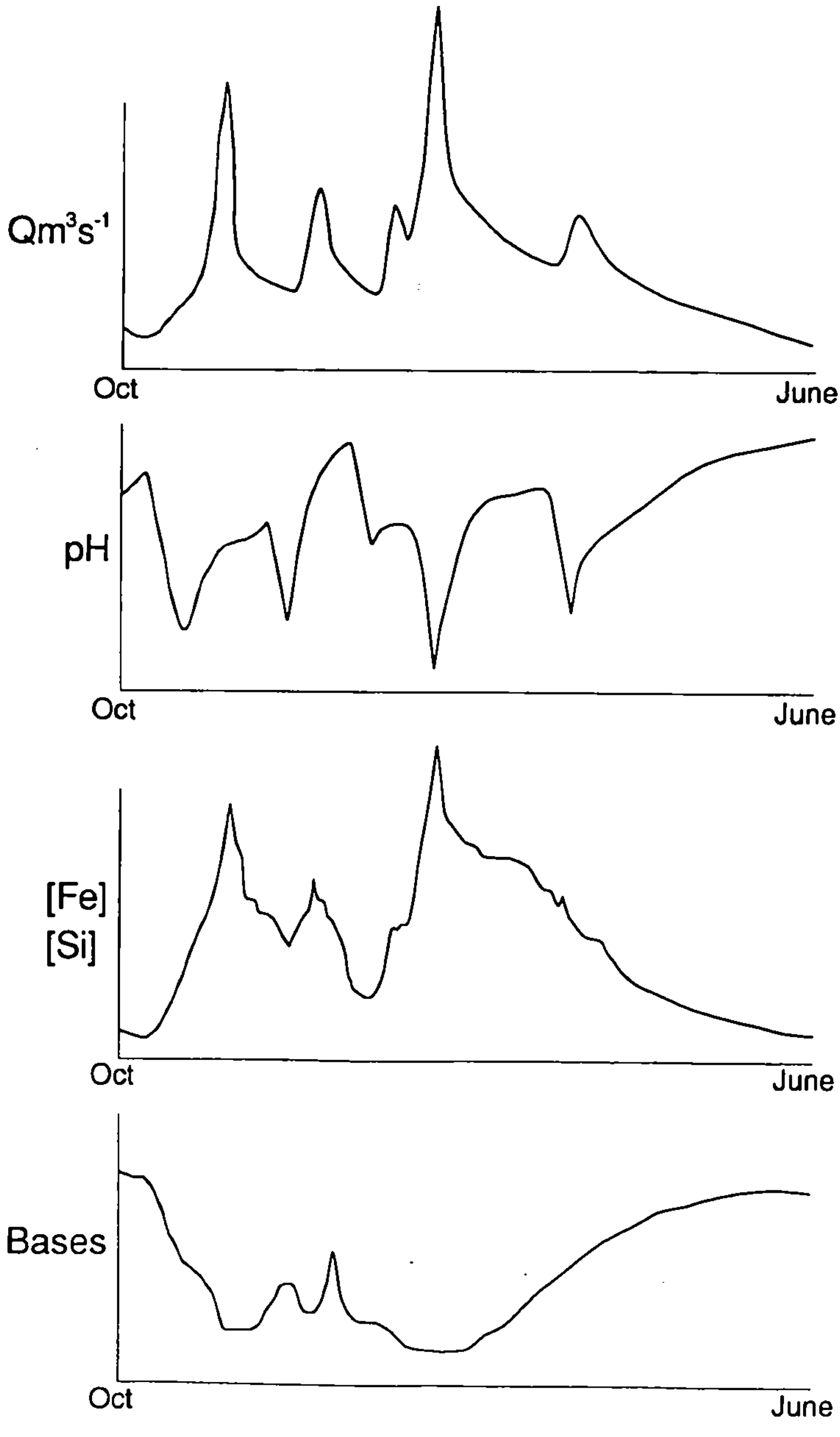


Figure 5. General pathways for major elements leached from the interfluve profiles of the African Surface in Malawi. Silica and bases, leached in the early stages of weathering in the lower parts of the profile, are carried in the deep groundwater system which discharges in to the *dambos*. Congruent kaolinite dissolution in the upper part of the profile releases Al and Si, which, together with Fe, are discharged into the *dambos* by shallow throughflow

Figure 12. Hypothesised variation in streamwater chemistry with changing pattern of flow



Appendix A

Concept notes submitted or incorporated in funding applications

NATURAL ENVIRONMENT RESEARCH COUNCIL

TERRESTRIAL AND FRESHWATER SCIENCES DIRECTORATE

PROPOSAL FOR NEW PROJECTS/SUBPROJECT (SCIENCE BUDGET)

INSTITUTE(S)/LOCATION(S)
Institute of Hydrology,
Wallingford.
University of Zimbabwe.

PROJECT LEADERS

Dr A Bullock
Dr R Owen

TFSD PROGRAMME

IF SUBPROJECT, NAME AND NUMBER OF EXISTING PROJECT

PROJECTS/SUBCONTRACT TITLE

The Dambo Process Integration Experiment - the dynamic relationships between hydrological/hydrochemical processes and dambo wetland/structure.

BRIEF DESCRIPTION OF PROJECTS/SUBCONTRACT (MAXIMUM 60 WORDS)

This project will simultaneously monitor hydrological and hydrochemical processes in the dambo/Basement Complex environment of Southern Africa for the first time. The linkages will be explored between different processes and wetland/dryland geomorphological structure. Maps of dambo boundaries in Malawi, Zambia and Zimbabwe will be imported into ARC/INFO, where association with existing hydrogeological and vegetation data will lead to a region-wide dambo classification scheme, that recognises internal dambo variations and associated geographical features. An existing representative gauged dambo catchment, representing one or more of the most extensive dambo types, will be monitored for spatial variation of evaporation, soil water content and tension and hydrochemistry. Data will be analysed in an integrated manner to quantify hydrological and chemical properties of the ecosystem components and identify hydrological pathways. The output will be a generic dambo hydrological and hydrochemical model, which can be used to simulate other dambo types, and thereby contribute to the increasingly critical debate on water management issues, and the determination of the role of dambos in controlling low river flows and sustainable agricultural exploitation, recognising the diversity of dambo properties.

START DATE

1/4/95

DURATION OF PROJECT/SUB PROJECT

4 years

PROJECT LEADER'S SIGNATURE AND DATE

INSTITUTE DIRECTOR'S STATEMENT

This proposal is targeted at several of the priority areas for scientific research identified by the recent NERC Expert Review Group on wetlands; notably (i) the relationships between structure and function; (ii) wetland hydrological field measurements and methods; (iii) wetland ecosystem processes related to function; (iv) the exploitation of remotely-sensed data. The proposal is advanced in combining contributions from different branches of hydrology, and thereby enforces the integration of specialists. The project addresses real problems of water resources exploitation and agricultural potential for rural communities. Because of the excellent links with organisations in Zimbabwe, the collaboration will function well, and the proposal receives my fullest endorsement.

	1995/96	1996/97	1997/98
Direct Staff Costs	25K	35K	55K
Direct Recurrent Costs			
(i) Travel and Subsistence	14K	16K	16K
(ii) Consumables	1K	1K	1K
(iii) Others (specify) - Water chemistry sampling equipment	4K	-	-
Direct Capital Expenditure	-	-	-
Direct Computing Charges	5K	2K	2K
Direct Institute Support Costs			
(i) Chemistry	14K	14K	14K
(ii) Remote Sensing	-	15K	-
(iii) Others (specify)	1K	1K	1K
Bought-in Services (from other Institutes or Outside) (specify)			
Total Direct Costs	64K	84K	89K

BACKGROUND

Dambos are seasonally-saturated, headwater, valley-bottom wetlands in Southern Africa. They cover approximately 10-15% of the land surface of several countries and exert a wide influence on the downstream hydrology of almost all of the principal rivers of the region. Particularly, dambos have been widely attributed the role of sustaining dry season river flows by releasing water from storage. This perceived, but scientifically unsubstantiated, function has resulted in legislation in Zimbabwe which prohibits the agricultural exploitation of dambos to protect downstream riparian rights. Flow regime analysis (Bullock 1992, a,b) and preliminary regional evaporation estimates from remote sensing (Stewart in British Geological Survey 1989) have shown that dambos actually reduce dry season flows by promoting evaporation where dambos occur in association with deep, permeable Basement regolith. In addition to their perceived, but challenged, economic value as regulators, dambos themselves represent a valuable resource for rural subsistence agriculture by small-scale irrigation (Faulkner and Lambert 1991), which broadly proceeds despite the legislation. The situation in countries such as Zimbabwe, Zambia, Malawi and Angola is equivalent to having a resource as extensive and as potentially valuable in water resource terms as the Chalk of Southern England, prohibited in its use by unresearched, but challenged, premises of hydrological function. Yet, the scientific evidence to explain the process functions of dambos remains fragile at this time.

The solution lies in understanding hydrological processes, both individually and in an integrated manner, in the dambo/Basement Complex environment, and by linking wetland processes to structure. A new model of hydrological pathways, based on the interpretation of geomorphological data, has been postulated by McFarlane and Whitlow (1990). However, in this case theory has outstripped hydrological data, and there is a need to validate the hypothesized system against hydrological data.

We make two hypotheses; first, it is hypothesized that water contributing to dry season river flows downstream of dambos is hillslope groundwater flowing beneath the dambos, and that there is no (or very minor) base flow water released from dambo storage. That there is a significant hydrological pathway beneath (and bypassing) the dambo is suggested by radically new explanations of dambo gully formation (McFarlane and Whitlow, 1990). That there is no base flow water released from dambo storage is suggested by zero estimates of the Base Flow Index for dambos (Bullock, 1992a). The hydrochemistry is the key to the resolution of this issue, because of the distinctive three-tier weathering profile of the granitic Basement Complex hillslopes (British Geological Survey, 1989). It is postulated that the dambo soil moisture store is recharged early in the wet season either by direct precipitation or by shallow throughflow from the upper residuum in the regolith profile. Because of its advanced stage of weathering, the residuum is leached of silica and bases and releases aluminium ions by congruent kaolinite dissolution. The water chemistry signature of the dambo water, and any river flow derived from the dambo, will reflect the origins of the water. It is postulated that water flowing beneath the dambo originates from deeper-recharged water which percolates through the residuum to the zones of superior weathered (vadose) and inferior weathered (phreatic) saprolite, which due to the less progressive weathering is the source of silica and the bulk of readily soluble materials (Na, Ca, Mg, K). The distinctive chemical composition of the groundwater will allow identification of the origins of dry season river flows. Further, isotopes of oxygen, hydrogen, carbon and nitrogen will identify the relative contributions of surface and groundwater. That dambos make only a minor contribution to dry season flows is argued by the postulation that dambo clays remain saturated throughout the dry season because of the high retentive capabilities, that the active store is small, and that stored water is lost principally to evaporation at potential rates under grassland.

The second hypothesis is that dambos reduce the groundwater contribution to dry season river flows by the promotion of evaporation losses. Dambos are proposed as riverine buffers which promote high dry season evaporation losses because of the low hydraulic conductivity (e.g. 10^{-2} m/d) compared with the hillslope (100 m/d) and the distinctive geomorphology of their marginal zones. That dambo margins have high evaporation losses has been suggested by analysis of Landsat TM data. The infra-red imagery was converted to surface temperature and thence to daily evaporation (Stewart in BGS, 1989). That dambos influence groundwater contributions to streamflow is suggested by the evidence that low flows are reduced in catchments with high proportions of dambo compared with catchments with low proportions (Bullock, 1992a).

OBJECTIVES

1. To identify whether the origin of dry season base flows in Southern African rivers derives from hillslope groundwater or from dambo wetlands.

2. To investigate whether dambos reduce the groundwater contribution to dry season river flows by the promotion of evaporation losses.

3. To develop a generic dambo model based on hydrological pathways and hydrochemistry.

4. To apply the generic dambo models to different environmental configurations, and catchment management practices to simulate river flow and water quality time series, which can be interpreted using statistics pertinent to water resource exploitation.

METHODOLOGY

Dambos have been delimited in plan form on 1:50,000 maps in Malawi, Zambia and Zimbabwe, and the boundaries will be transferred to ARC/INFO where association with other existing hydrogeological, soil and vegetation databases will enable the construction of a dambo classification scheme. A representative gauged small dambo catchment (<5 km^2) representing one of the major dambo types on a Research Station in Zimbabwe, already possessing 20 years of rainfall and flow data, will be instrumented and monitored over a period of 42 months comprising an experimental period of 30 months and a validation period of 12 months. Monitoring will comprise micrometeorology, rainfall chemistry/hydrology, groundwater levels and chemistry, dambo soil moisture and chemistry and river flow chemistry/hydrology. Water chemistry, will be analysed for pH, EC, major anions and cations, selected trace metals and isotopes of oxygen, hydrogen, carbon and nitrogen. Data will be analysed using input-output, time series and various statistical and hydrochemical techniques.

Dambo soil moisture content and tension will be monitored at different depths at the dambo margins and within the dambo to identify the origins of dambo-recharging water through the response to rainfall and throughflow. Hydrological and hydraulic properties, particularly hydraulic conductivity, of the dambo and regolith will be determined.

During a period of at least one year the temporal and spatial variation in the evaporation from one or more dambos and the surrounding area will be studied. Thermal infra-red data acquired by the Landsat satellite will be converted into surface temperature measurements using ground-based infra-red thermometer measurements to correct for atmospheric effects. The satellite measurements will be combined with ground-based measurements of air temperature to derive the spatial variation of the difference between surface and air temperature. Since air temperature shows little spatial variation over areas with little topography, air temperature measured at one site is representative of a large area. From the difference between surface and air temperatures one of the major atmospheric turbulent fluxes, the sensible heat flux, can be determined. Using the ground-based measurement of net radiation with the measurement of the sensible heat flux, the evaporation can be determined as the residual. The size of the surface-air temperature difference indicates whether evaporation is limited by the availability of soil water or energy. When there is a plentiful supply of soil water, evaporation is close to the potential rate, and the surface-air temperature difference is small. The potential evaporation rate can be estimated from standard formulae (Penman or Priestley-Taylor) using automatic weather station data. When the surface-air temperature difference is large, evaporation is limited by the availability of soil moisture and is an unknown fraction of the potential rate. Surface temperature data can only be obtained from Landsat when the area is cloud free. Since Landsat passes over a particular area every 16 days it is hoped that 8 to 12 sets of data will be obtained during one year.

In parallel with instrumentation and monitoring, a generic dambo computer model will be developed based on the University of Minnesota Peatland Hydrologic Impact Model (Guertin *et al.* 1987). This model will be modified to initially take account of the hydrological model postulated by McFarlane and subsequently the results of the process data. Twelve months of monitored data will be used to validate the generic dambo model in terms of predicted streamflow and chemistry. The model will be further validated against the existing 20 years of observed rainfall, evaporation and river flow data.

The model will be applied under different environmental configurations which represent variations in the structure of the dambo/Basement Complex association to predict river flow and chemistry series, with validation of flow series against existing gauged flow series from catchments representing other dambo and catchment types. The significance (and economic value) of the dambo function will be expressed in statistics relevant to water resource planning.

PREVIOUS WORK

Water chemistry and hydraulic properties of dambos and Basement regolith have been measured in Malawi (BGS, 1989). Small hydrological experiments in gauged catchments have been undertaken in Zambia (Balek and Perry, 1973) and Zimbabwe (Faulkner and Lambert, 1992) and have been operated for over two years at Marondera by the University of Zimbabwe, where the proposed activities are focussed. However, the different hydrological disciplines have not been combined within an integrated experiment. Very little process work has been directed towards dambos, which have been treated essentially as black-box elements in a hydrological system. Stewart has demonstrated the spatial variability of evaporation within dambos (BGS, 1989). Water chemistry has been used for hydrograph separation in acidic upland environments, but has not been employed in the widely occurring granitic Basement Complex.

STRATEGIC IMPORTANCE

This project, for the first time, will combine a number of hydrological disciplines in the study of tropical wetland processes and thereby ensure the integrated explanation of different types of data. This activity will contribute to the linking of wetland function and structure. This instrumented catchment approach will extend methods originally developed for temperate climates to tropical climates. Moreover, it is a tropical environment that is representative of a wide region which faces difficult water management issues. The investment in primary data collection and the fundamental science of integrated process investigation should provide NERC and its collaborators funding opportunities in the arena of tropical wetlands. In an applied context, the project will answer strategic questions regarding i) the extent of the dambo resource in Southern Africa, ii) variations in the nature of the dambo resource, iii) the role (and its variations) of dambos in determining dry season flows with implications for Water Law and downstream riparian abstractors (where water rights are under increasing pressure), iv) the hydrological sustainability of agricultural exploitation of dambos and v) hydrological basis of integrated catchment management plans. These issues have been identified as key questions by the responsible basin management authorities in countries with a significant dambo resource.

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Balek, J. and Perry, J.E. (1973) Hydrology of seasonally inundated African headwater swamps. J. of Hydrol. 19: 227-249.

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Bullock, A. (1992a) The role of dambos in determining river flow regimes in Zimbabwe. J. of Hydrol. 134: 349-372.

Bullock, A. (1992b) Dambo hydrology in Southern Africa review and reassessment. J. of Hydrol. 134: 373-396.

Faulkner, R.D. and Lambert, R.A. (1991) The effect of irrigation on dambo hydrology: a case study. J. of Hydrol., 123: 147-161.

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ODA-TDR.MPM

ODA ENGINEERING DIVISION
TECHNOLOGY DEVELOPMENT AND RESEARCH (TDR) PROGRAMME

IH INTERNAL CONCEPT NOTE FOR INITIAL PROJECT SELECTION
[Deadline for return to Henry Gunston - Friday 22 July]

PLEASE ENSURE THAT YOUR NOTE DOES NOT EXCEED THREE PAGES.

PROJECT TITLE: Management of soil and water resources in headwater catchments in Southern Africa

PROPOSER: Matthew McCartney and Andy Bullock

PROJECT DESCRIPTION Hydrological and socio-economic investigation, to assess ways of improving the utilization of headwater catchments in Southern Africa.

ODA SUBSECTOR: Water and sanitation

SUBSECTOR THEME: Improve availability of water for sustainable food production and rural development.

ESTIMATED DURATION: April 1995 - March 1998

ESTIMATED IH COST: £300k

PROJECT OBJECTIVES:

Seasonally inundated headwaters (dambos) in the ancient cratonic areas of Southern Africa are predominantly uncultivated and it is suggested constitute an underutilized agricultural resource (McFarlane and Whitlow, 1991). However, this resource may be fragile and its nature must be fully understood so that the limits within which use is possible without causing irreversible damage can be ascertained. Furthermore the likely impact of possible increases in water use within headwater catchments on downstream water users must be established.

The principal objectives of this study will be:

- To increase our understanding of catchment hydrological processes and the physical impact of different soil and water conservation measures within headwater catchments.
- To determine methods of optimising water use and reducing soil erosion.
- To provide baseline data that will assist planners in placing headwater resource management within an integrated administrative framework, thereby ensuring that the interests of downstream water users are not jeopardized.

It is intended that this study will provide recommendations on appropriate catchment management strategies that if implemented would improve the condition and livelihoods of peasant farming communities residing in the headwater catchments of communal land regions of Zimbabwe and similar areas in Malawi and Zambia.

BACKGROUND:

Within the SADCC region the current population of about 84 million is growing at a rate of approximately 3% per annum. Many people in the region have experienced a decline or stagnation in living standards since 1980. Significant increases in food agricultural productivity will be required to improve food security and the quality of life (World Bank, 1994).

Dambos are widespread in central and southern Africa, occupying about 10% of the total land surface. Many dambos retain extensive wet regions during the dry season and it is the availability of water in otherwise dry areas that make dambos a potentially valuable resource. Prior to European colonization the use of dambos for the cultivation of crops was a long established indigenous land-use practice enabling year round crop production since gardens could be hand-irrigated in the dry season from shallow wells excavated at their margins. In the early 1900's European farmers were quick to exploit the 'turf-like' soils in dambos because they were easily ploughed and the high moisture retention allowed cropping in the dry winter months. However, European agricultural practices (e.g. the introduction of drainage ditches) resulted in accelerated gullying of dambos on commercial farms and the belief that all cultivation of dambos was *bad* became widespread.

In order to protect the widely perceived role of dambos in regulating downstream flows the colonial government introduced legislation in the 1950's curtailing dambo cultivation, even in indigenous farming areas. As a direct result of this legislation progressively greater areas of the interfluves (dryland regions surrounding dambos) were deforested and taken over for dryland cultivation. Crop production is now predominantly rain-fed and consequently local populations are at risk from poor wet seasons.

It has been suggested that the shift from dambo to interfluve cultivation intended to protect dambos has instead made the situation worse, because raised water tables below deforested interfluves promote gullying. Furthermore, there is increasing evidence that in environmental terms, the traditional small-scale methods of cultivation were not as damaging as the introduced European methods for two reasons: a) the patchwork of basins, ridges and furrows minimized runoff; b) the disturbance of the soil profile was only very shallow (McFarlane and Whitlow, 1991). Recent scientific research also suggests that the role of dambos on dry season flow regulation may be less than was previously suspected (Bullock, 1992) and that *within limits* dambos may offer significant potential for an expansion in irrigated cultivation (Faulkner and Lambert, 1991).

Since population densities are growing rapidly and enforced soil conservation measures are increasingly being seen to fail there is now a need to develop alternative approaches to the management of headwater areas. It is essential that appropriate methods of soil and water resource management are introduced that both protect these fragile environments and produce a quantifiable benefit to the local population. In addition, introduced schemes should not adversely affect downstream water users. To be successful developed management strategies must take into account the nature of the socio-economic environment (e.g. social structure, land tenure and market linkages etc.). Clearly, an integrated approach to resource management must be developed.

WORK PLAN:

IH has wide experience of both process and catchment scale studies. It is proposed that three instrumented catchments are established in Zimbabwe in order to ascertain how the nature of the physical environment (vegetation, soils, topography etc.) influences the hydrology and the production potential of headwater catchments. One catchment, left in its natural state, would be used as a control while the other two would be used to investigate the range of appropriate (i.e. socially and economically acceptable) technologies that might be used to increase yield and prevent soil erosion. For example different methods of irrigation, contour bunding and water harvesting techniques will be investigated. Within each catchment an automatic weather station as well as networks of raingauges, soil moisture stations, tensiometers, piezometers and streamflow gauging stations will be established to determine catchment soil and flow regimes. Sediment sampling programs will be initiated to determine small-scale plot and catchment sediment yields. The impact of different land-use and management practices on the soil moisture regime, erosion and downstream flows will be ascertained.

In parallel with the hydrological investigation, socio-economic studies, actively involving local people, and similar to those presently being conducted by IH in the dryland regions of southern Zimbabwe will be carried out to evaluate the practicality of improved land management practices. This will include evaluation of institutional aspects of catchment management.

COLLABORATORS: University of Zimbabwe, Department of Research and Specialist Services, Zimbabwe, Non-Governmental Organisations (NGOs)

REFERENCES:

Bullock A. (1992) The role of dambos in determining river flow regimes in Zimbabwe. Journal of Hydrology, 134: 349-372

Faulkner R.D. and Lambert, R.A. (1991) The effect of irrigation on dambo hydrology: a case study. Journal of Hydrology, 123: 147-161.

McFarlane M.J. and Whitlow R. (1991) Key factors affecting the initiation and progress of gullying in dambos in parts of Zimbabwe and Malawi. Land Degradation and Rehabilitation, 2: 215-235.

World Bank (1994) Agricultural Research in Southern Africa: A Framework for Action - A World Bank Discussion Paper.

ODA ENVIRONMENTAL POLICY DEPARTMENT
ENVIRONMENTAL RESEARCH PROGRAMME (ERP)

CONCEPT NOTE

PROJECT TITLE:	Management of soil and water resources in headwater catchments in Southern Africa
PROPOSER:	Matthew McCartney (IH), Andy Bullock (IH) and Richard Owen (University of Zimbabwe)
PROJECT DESCRIPTION:	Hydrological investigation, to assess the environmental consequences of agricultural practices in headwater catchments in Southern Africa.
ODA ERP THEME:	Research targeted on localised environmental problems associated with .... the degradation of environmentally sensitive habitats.
ESTIMATED DURATION:	April 1995 - March 1998
ESTIMATED COST:	£300k

PROJECT OBJECTIVES:

Seasonally inundated headwaters (dambos) in the ancient cratonic areas of Southern Africa are predominantly uncultivated and it is suggested constitute an underutilized agricultural resource (McFarlane and Whitlow, 1991). However, dambo soils are relatively thin and prone to gullying. Consequently the physical process operating within these headwater wetland areas must be fully understood so that the limits within which they may be used, without causing irreversible damage can be ascertained. Furthermore the likely impact of possible increases in water use within headwater catchments on downstream water users must be established for the consolidation of catchment management plans.

The principal objectives of this study will be:

- To increase our understanding of catchment hydrological processes and the physical impact of different soil and water conservation measures within headwater catchments.

- To determine methods of optimising water use and reducing soil erosion.

- To provide baseline data that will assist planners in optimising the agricultural productivity of headwater catchments, as well as protecting the environment and ensuring that the interests of downstream water users are not jeopardized.

It is intended that this study will provide results that will assist decision makers in drawing up appropriate catchment management strategies. These will both improve the condition and livelihoods of small-scale farming communities residing in headwater catchments and at the same time protect the dambos from the effects of land degradation caused by misuse.

BACKGROUND:

Within the SADC region the current population of about 84 million is growing at a rate of approximately 3% per annum. Many people in the region have experienced a decline or stagnation in living standards since 1980. Significant increases in agricultural productivity will be required to improve food security and the quality of life (World Bank, 1994).

Dambos are widespread in central and southern Africa, occupying about 10% of the total land surface (an area greater than the combined area of England and Wales). Many dambos retain extensive wet regions during the dry season and it is the availability of water in otherwise dry areas that make dambos a potentially valuable resource. Prior to European colonization the use of dambos for the cultivation of crops was a long established indigenous land-use practice enabling year round crop production since gardens could be hand-irrigated in the dry season from shallow wells excavated at their margins. In the early 1900's European farmers were quick to exploit the 'turf-like' soils in dambos because they were easily ploughed and the high moisture retention allowed cropping in the dry winter months. However, European agricultural practices (e.g. the introduction of drainage ditches) resulted in accelerated gullying of dambos on commercial farms and the belief that all cultivation of dambos was detrimental became widespread.

In order to protect the widely perceived role of dambos in regulating downstream flows the colonial government introduced legislation in the 1950's curtailing dambo cultivation, even in indigenous farming areas. As a direct result of this legislation progressively greater areas of the interfluves (dryland regions surrounding dambos) were deforested and taken over for dryland cultivation. Crop production is now predominantly rain-fed and consequently local populations are at risk from poor wet seasons and rapid losses of fertility.

It has been suggested that the shift from dambo to interfluve cultivation intended to protect dambos has instead made the situation worse, because raised water tables below deforested interfluves have been linked to the iniation of gullying. Furthermore, there is increasing evidence that in environmental terms, the traditional small-scale methods of cultivation were not as damaging as the introduced European methods for two reasons: a) the patchwork of basins, ridges and furrows minimized runoff; b) the disturbance of the soil profile was only very shallow (McFarlane and Whitlow, 1991). Recent scientific research also suggests that the role of dambos on dry season flow regulation may be less than was previously suspected (Bullock, 1992) and that *within limits* dambos may offer significant potential for an expansion in irrigated cultivation (Faulkner and Lambert, 1991).

Since population densities are growing rapidly and enforced soil conservation measures are increasingly being seen to fail there is now a need to develop alternative approaches to the management of dambos. The wise use and conservation of dambos has recently received increasing attention, indeed in Zimbabwe a Wetlands Conservation Programme has recently been initiated, and it is generally recognized that baseline data that can be used to determine appropriate methods of soil and water resource management must be obtained. Strategies must be developed that both protect these fragile environments and produce a quantifiable benefit to the local population. In addition, introduced schemes should not adversely affect downstream water users. Clearly, an integrated approach to resource management must be