4

SWIM Paper

Improving Water Utilization from a Catchment Perspective

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SWIM

IWMI

System-Wide Initiative on Water Management

SWIM Papers

In an environment of growing scarcity and competition for water, increasing the productivity of water lies at the heart of the CGIAR goals of increasing agricultural productivity, protecting the environment, and alleviating poverty.

TAC designated IWMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IWMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is strong complementarity between their work and many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

The initial publications in this series cover state-of-the-art and methodology papers that assisted the identification of the research and methodology gaps in the priority project areas of SWIM. The later papers will report on results of SWIM studies, including inter-sectoral water allocation in river basins, productivity of water, improved water utilization and on-farm water use efficiency, and multiple uses of water for agriculture. The papers are published and distributed both in hard copy and electronically. They may be copied freely and cited with due acknowledgment.

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SWIM Paper 4

Improving Water Utilization from a Catchment Perspective

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The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read as International Water Management Institute (IWMI).

Contents

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Abstract

The System-Wide Initiative on Water Management (SWIM) has defined its central theme and objective as “enhancing the productivity of water and agriculture in an environment of growing scarcity and competition.” One program area of SWIM, namely SWIM 7, has the aim of improving the utilization of water resources from the catchment perspective. This paper has been prepared as part of the process of planning research that is to be undertaken by SWIM 7. The paper includes a historical review of research that has involved the use of catchment experiments and a discussion on hydrological modeling techniques. Options for improving water utilization at the catchment and farm scales are identified, and recommendations are made for research that might be undertaken by SWIM 7. The case is argued for interdisciplinary catchment studies that involve the participation of local communities and other stakeholders.

Improving Water Utilization from a Catchment Perspective

Charles Batchelor, Jeremy Cain, Frank Farquharson, and John Roberts

Introduction

Traditionally, the main aims of hydrological research have been to provide an understanding of the water balance operating in catchments,[1] the processes and mechanisms that control water movement, and the impacts of land use change on water quantity and quality. In recent years, however, a more interdisciplinary approach has been taken for the design and implementation of hydrological or "catchment" research programs. Increasingly, these programs are tackling broader objectives related to improving the management of water and other natural resources, reducing environmental degradation and promoting sustainable development. These programs involve researchers from a wide range of disciplines (e.g., hydrology, agriculture, forestry, economics, social and institutional development, etc.), local institutions, farmers, extension workers, and other stakeholders. Emphasis is placed on understanding the physical, economic, social, political, and institutional driving forces that influence production, resource use, economic activity, and welfare at different scales within catchments.

This paper provides a brief historical review of hydrological and "catchment" research programs with an emphasis on research that has been carried out in Africa. To detail the approaches that have been or could be used, a comparative review is also provided of modeling techniques that are being used in hydrological and "catchment" research. The paper continues by discussing approaches that can be used to improve the efficiency of water utilization at the catchment and sub-catchment scales. Finally, some suggestions are made on "catchment" research that might be undertaken as part of the SWIM Initiative.

Review of Catchment Research Projects

Pioneering Catchment Experiments

The concept of the hydrological cycle now seems so obvious and simple, it is incredible that it was only some 300 years ago that Perrault's (1674) study of the basin of the River Seine led to this understanding. A study of ancient civilizations indicates that mankind has been well versed in the use and management of water for millennia. Hence, water management and irrigation technology preceded the science of hydrology by thousands of years (McCulloch and Robinson 1993).

[1] British usage of the words "catchment" and "watershed" refer to the area that catches runoff and the boundary of this area, respectively.

Studies of the importance of catchment characteristics and, in particular, land use upon river flows began at the end of the last century (Whitehead and Robinson 1993). After a series of disastrous Alpine floods in the 1860s and 1870s, it was recognized that, if a sound basis were to be given to a policy of reafforestation and rehabilitation of mountain lands, investigations would be necessary to identify the role played by deforestation. This led to the establishment of the first modern catchment study in 1902 in the Emmental region of Switzerland, where two catchments, the mainly forested Sperbelgraben and the mostly pasture Rappengraben, were instrumented (Engler 1919). The catchments are each approximately 0.6 km^2 in area and have approximately 1,650 mm $year^{-1}$ precipitation. Results indicated that flood flows and annual yields were lower from the forested catchment while base flows were higher. Although doubts have subsequently been expressed regarding the quality of the data (Penman 1959), the principle of the benefits of forest protection and rehabilitation in mountainous areas had been established (Keller 1988).

At about the same time, catchment studies were established in other countries, of which the best known is the paired catchment study near Wagon Wheel Gap in southern Colorado, USA (Whitehead and Robinson 1993). There, instead of simply comparing directly flows from two catchments, which were assumed to be similar in all respects except vegetation cover, a change in land use was imposed on one catchment during the study and the other catchment was kept unchanged as a "control." The area of the catchments is about 0.9 km^2 and the soils are deep, permeable, and coarse-textured. Almost half of annual precipitation falls as snow. After an 8-year calibration period the forest in one basin was cut down and subsequent changes in stream flow relative to that of the untouched control catchment were ascribed to the removal of trees (Bates and Henry 1928). It was concluded that the forest removal increased stream flow by approximately 30 mm $year^{-1}$ over the following 7 years, mostly as higher spring flood discharge and also as a small increase in summer low flows. The importance of these results of plentiful winter snow and the deep permeable soils was stressed.

This experimental design, in which changes may be studied by comparison of the flow regimes before and after deforestation with those of a "control" catchment, was adopted in many later studies. It has the advantage of reducing the effects of year-to-year climatic variability, as both catchments are affected by the same climatic factors. In general, the "calibration" period is used to quantify the influence upon flows of differences between the two catchments in, for example, geology and topography.

A great many catchment studies with measurements of precipitation and stream flow were initiated during the 1920s and 1930s. These investigations were considered necessary because, it was assumed that relationships between participation, stream flow, and land use change would be influenced by a range of site-specific conditions (including climate, topography, and soils). Possibly the most comprehensive study has been that at Coweeta, which is located in North Carolina, USA. It was selected in the early 1930s as a suitable site for forest impact studies and is reputed to be the oldest continuously operating catchment study in the world (Swank and Crossley 1988). Coweeta is a headwater drainage basin of about 18 km^2 in a high rainfall area (around 1,800 mm $year^{-1}$) with deep soils and a complete forest cover (mainly hardwoods). Experimentation on over 20 individual sub-catchments has included clear felling and replanting. Some of the main hydrological findings were as follows:

- Clear-cutting increased mean storm flow and peak flow rates by about 15 percent.
- Natural alteration of vegetation, such as insect defoliation, influenced water yield by stimulating leaf production and increasing evaporation, thus reducing winter stream flow by between 7 percent and 18 percent.
- The long-term experiments showed the strong dependence of stream flow volumes on forest type.
- Hardwood to pine conversion reduced runoff by 250 mm year^{-1}.
- Hardwood to grass conversion also altered stream flow.
- Depending on grass productivity a decline in growth of grass led to increase in stream flow.

Finally, one of the main hydrological conclusions from Coweeta was that forest managers should recognize that silvicultural prescriptions affect both transpiration and interception, and hence stream flow.

Table 1 provides a simplified summary of results from early catchment studies. These pioneering catchment studies proved to be invaluable for engineering design purposes (e.g., estimating floods, reservoir yield calculations). However, it was recognized, particularly in the 1960s, that detailed hydrological process studies were needed within catchments to improve interpretation of results and to enable extrapolation of results from one catchment to another.

TABLE 1.
Simplified summary of main hydrological effects of forestry from basin experiments (after Whitehead and Robinson 1993).

Site	Type of study	*Stream flow changes caused by forest (decrease - ↓, increase - ↑, no difference - nd)		
		Annual	Peaks	Base flow
Emmental	C	↓	↓	↑
Wagon Wheel Gap	D	↓	↓	↓
Coweeta	D	↓	↓	↓
Hubbard Brook	D	↓	↓	↓
Plylimon	C	↓	nd	nd
Jonkershoek	A	↓	↓	↓
E.Africa	D	↓	↓	↓
H.L.Andrews	D	↓	↓	↓
Coalburn	A	↑	↑	↑

*Afforestation (A); deforestation (D); comparison between catchments (C).

Pioneering Catchment Experiments in Eastern and Southern Africa

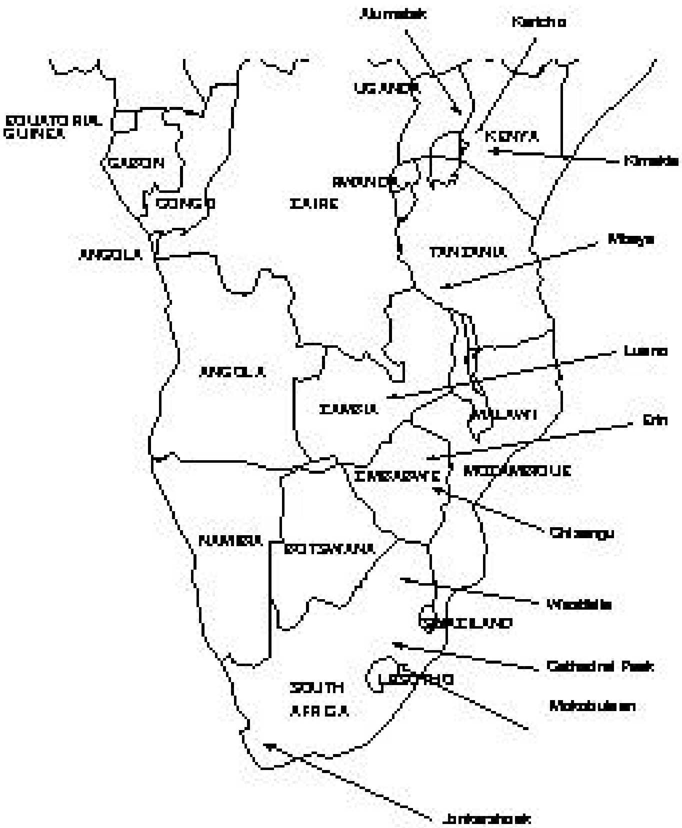
In the belief that forests protect upland environments, substantial areas in East Africa had been designated as forest reserves under colonial rule (McCulloch and Robinson 1993). These high altitude forests had been "closed" to settlement or grazing not because of the commercial value of the remnants of montane forest but as a kind of land bank to protect the soils from erosion and to preserve the dry weather stream flow on which the downstream populations were entirely dependent.

As growing populations increased the pressure on existing agricultural land, a series of catchment studies was initiated to seek answers to social and political questions related to the hydrological consequences of land use change in upland areas. A study concerned with the development of indigenous forest into tea plantation was set up at Kericho in Kenya and a second concerned with a change to pine tree plantation was set up at Kimakia also in Kenya. The improvement of eroded pastures in dryland areas and the effects of primitive cultivation on steep hillsides were investigated at Atumatak and Mbeya in Tanzania, respectively. The location of these experiments is shown in figure 1 and results from these experiments are summarized by McCulloch and Robinson (1993) and discussed in more detail by Pereira (1962); Blackie, Edwards, and Clarke (1979); and Edwards and Blackie (1981). In addition to reporting the effects of land use change, it was shown that rainfall interception, infiltration rates, and the control on transpiration rates exercised by soil moisture deficits were all key hydrological processes.

In South Africa, high rainfall areas of the escarpment of the interior plateau and the mountains of the southern and southwestern coastlines were identified as having high potential for the establishment of exotic timber plantations. However, it is in these regions that many of South Africa's prime water supply catchments are situated. Consequently, since the 1930s, conflicts have existed between the timber industry and downstream water users. This conflict of interests provided the catalyst for an intensive forest hydrology research program. This program, which involved the establishment of research studies at Jonkershoek, Mokobulaan, Cathedral Peak, and Witklip (see figure 1) has, over the years, provided valuable information on the hydrological implications of afforestation and the management of natural vegetation. It was estimated that as a result of commercial afforestation, the surface water resources of South Africa were reduced by 1,284 million m^3 $year^{-1}$ in 1980 and a further reduction down to 1,700 million m^3 $year^{-1}$ was expected by the year 2010 (Department of Water Affairs 1986). This was calculated as a 32 percent increase in water use attributable to afforestation (Bosch and von Gadow 1990). A review of the aims, objectives, research methodologies, and findings of catchment studies in South Africa can be found in Andrews and Bullock 1994.

In Zambia, exploitation of woodlands by agricultural expansion and charcoal burning necessitated the instigation of the Luano Experimental Catchment Project to assess the effects of deforestation and subsistence agriculture on hydrological characteristics and water regimes. This project was initiated in 1964 as part of the Kafue River Multipurpose Survey. In Zimbabwe, two experiments on paired catchments

FIGURE 1.
Location of experimental catchments in eastern and southern Africa (after Andrews and Bullock 1994).



were started in the Erin Forest Reserve and the Chisengu Forest Reserve in 1958 and 1955, respectively, to study the effects of afforestation on stream flow and water supply (Andrews and Bullock 1994).

Pioneering Catchment Studies in Asia and Other Areas of Africa

Dubreuil (1986) provides a review and inventory of hydrological research undertaken by French hydrologists in tropical regions during the previous 30 years. The majority of the catchment studies reported were in semiarid western Africa (33 catchments); however, results were also reported for humid areas of western Africa, for Tunisia, and for Madagascar. These studies evaluated the influence of drainage area, slope, soil cover and soil surface conditions on runoff and, in particular, floods. The type and density of vegetation cover and the presence of soil crusts were identified as playing significant and often dominant roles.

Bruijnzeel (1990) reviewed the state of knowledge on the hydrology of tropical forests and the effects of conversion of forestland to other uses. This excellent review also summarizes the results of catchment studies that have been carried out in many parts of Asia. An important conclusion of this review is that the "adverse environmental conditions so often observed following deforestation in the humid tropics are not so much the result of deforestation per se but rather of poor land use practices after clearing the forest." More recent experiences gained from, in particular, participatory catchment management programs have been reported in the Asian WATMANET Newsletter.[2]

General Comments on Pioneering Catchment Studies

The pioneering catchment studies were very successful in providing the scientific information that should have dispelled the misinformation, misunderstanding, and myths about the role of forests with regard to hydrology, erosion, and the implications of removing or altering forest cover. Unfortunately, many myths and misconceptions continue to be the basis of much policy and decision making. A number of authors (e.g., McCulloch and Robinson [1993]; Bruijnzeel [1990]; Calder [1997]) detail and discuss some of the common misconceptions concerning forest hydrology.

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One problem related to the design of catchment experiments that were planned, say, for a duration of about 20 years, could have been that they outlived the socioeconomic considerations which gave rise to them in the first place (McCulloch and Robinson 1993). In fact, many of the pioneering catchment experiments were sufficiently well conceived that they ended up providing results and data that were more comprehensive than was envisaged at the outset. This said, it should be recognized that there are a number of common characteristics of these early studies:

- Most of them were located in upland headwater catchments.

- The main emphasis was on tackling issues related to surface water resources and land use change.

- As the emphasis was on surface water resources, few studies were located in dryland areas in which the assessment of groundwater resources becomes more important and in which environmental degradation and sustainable development are the main issues.

- The majority were located in upland areas where population densities were low as opposed to lowland areas where population densities may be higher and where land use and land management issues may be more complex.

- The majority concentrated entirely on the collection of hydrological data with little attention being given to the collection of data related to, say, agricultural production, economics, social development, or institutional development.

- Few projects involved the participation of farmers, local communities, or other stakeholders.

In summary, only a few catchment studies have been initiated in the dryland areas of the tropics where competition for water resources is most extreme and where environmental degradation and sustainable development are the main issues.

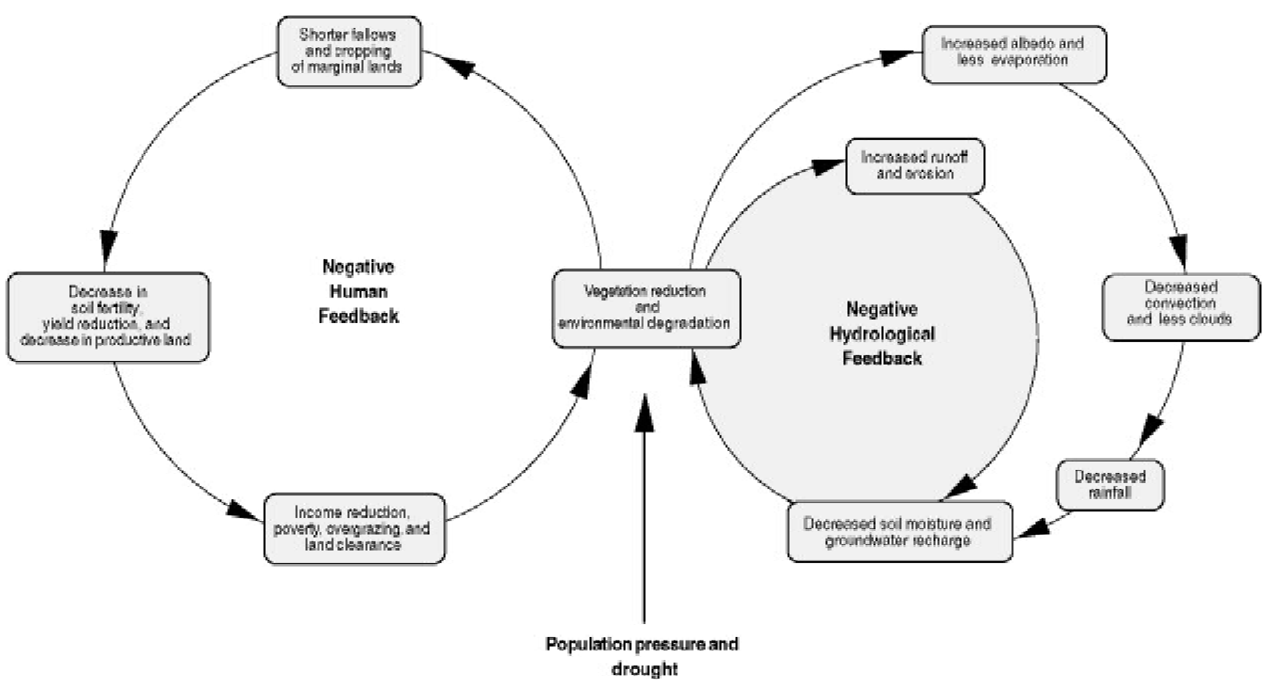
Romwe Catchment Study

An important first step in reversing environmental degradation and promoting sustainable agricultural development is the identification of the root cause (or causes) of degradation and poor resource management. It has to be recognized that changes in the environment are often the net effect of many different actions. General relationships between environmental trends and agricultural practice or land use may hide the true patterns of cause and effect. Moreover, many land use and environmental changes may exhibit parallel time trends that are nevertheless causally unrelated. It is all too easy, therefore, to make false interpretations on the basis of spurious correlations.

The exact nature of the economic, social, and physical feedback mechanisms that lead to environmental degradation has been under debate for many decades (Thomas and Middleton 1994). One shortcoming of many attempts to identify key feedback mechanisms has been the fact that they have not recognized that social and economic (or human) feedback mechanisms can take place at the same temporal and spatial scales as physical feedback mechanisms and that the items of feedback are often mutually reinforcing. Thomas and Middleton (1994) proposed feedback cycles, based on Scoging 1991, which acknowledge the intimate links between human and physical feedback. Figure 2 is based on this work.

The Romwe Catchment Study in Zimbabwe is an example of a research project that has been set up in a dryland area to study issues related to environmental degradation and sustainable development. This study began in 1992 with the objective of quantifying effects of changes in land use and management on groundwater recharge in dryland areas underlain by basement complex geologies. A small catchment (approximately 5 km^2 in area) in a communal area of southeast Zimbabwe was instrumented with the active participation of the local community and local institutions. The fact that the Romwe Catchment is the location of the first off-station collector well garden (Batchelor et al. 1996) was a major contributing factor in encouraging the communities in the catchment to participate in the study. In addition to instrumenting the main catchment, instrumentation was installed in three sub-catchments that represented *miombo* (sparse forest, characteristic of Southern Africa) forest and arable areas underlain by two soil types (a red sandy clay and a gray sandy loam over clay). Figure 3 is an example of hydrological data that have been collected. This figure, which

FIGURE 2.
Negative feedback mechanisms that lead to environmental degradation.

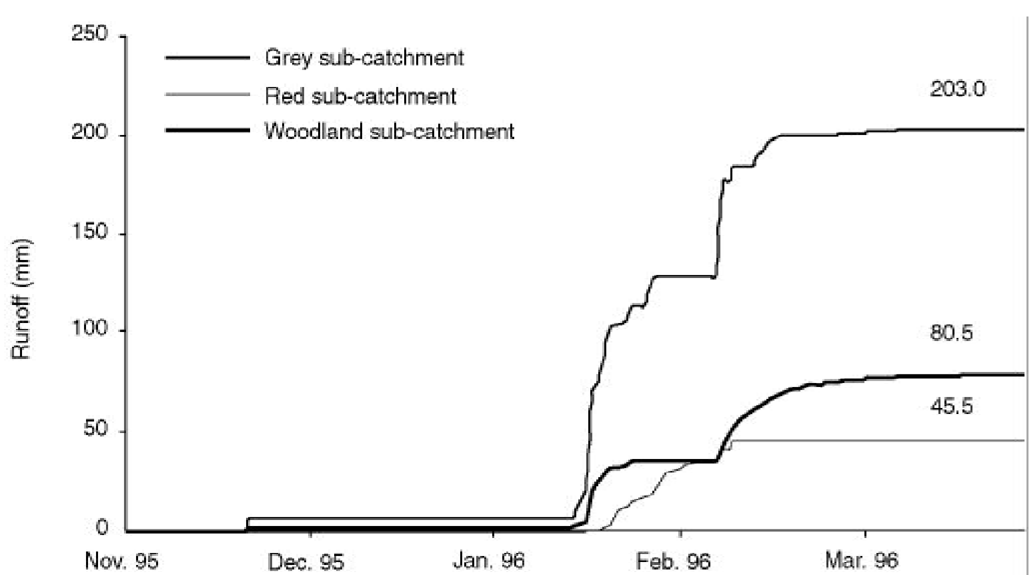


shows the very large difference in runoff between a wooded sub-catchment and one of the arable sub-catchments, gives an indication of the significant impact land use changes can have on the hydrology in this area. Butterworth (1997) discusses hydrological findings from the first 3 years of the study in detail.

A key hypothesis of the Romwe Catchment Study is that a first *productive water point* (i.e., collector well and community garden) can provide an ideal initial step towards other community-based activities aimed at reducing environmental degradation and promoting sustainable development. Ongoing work is aimed at testing this hypothesis and identifying the key steps needed to establish community responsibility for, and management of water and other natural resources. Evidence to date suggests that the immediate benefits from *productive water points* are sufficient to encourage communities to overcome the inevitable leadership and organizational problems associated with first community-based activities. Evidence to date also shows that *productive water points* have a positive impact on the wider farming and livelihood systems (Waughray et al. 1997). Time will tell whether collective responsibility will extend to protecting and sustaining the environmental resources needed to maintain the flow of benefits from the *productive water points*. One good sign is that collective responsibility is being exercised in the maintenance of pumps. In contrast to community-based water sanitation projects in southeast Zimbabwe, pumps on the collector well schemes are being maintained and repaired by the users.

A number of researchers have identified the conditions under which joint management of common property can be

FIGURE 3.
Cumulative runoff from two cultivated sub-catchments with contrasting soil types and a woodland sub-catchment for the 1995/96 period (after Lovell et al. 1997).



successful (e.g., Wade 1987; Evans 1996). These conditions are related to both the resource and the user group. They include:

- The resource is small and clearly defined.
- There is a close physical proximity between the resource and the users.
- The users have a high level of dependence on the resource.
- A small and defined set of users has already established arrangements for discussing common problems.
- Decision-making power within the user community is in the hands of subgroups favoring communal action.
- Cheating with regard to resource use is easily noticed.
- The costs of exclusion from the resource are high.

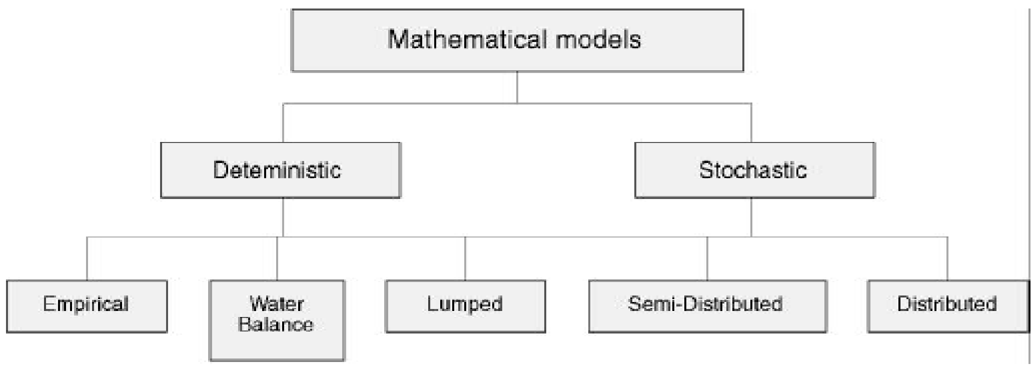
It is clear that most of these conditions either prevail or can be created when implementing *productive water points* in dryland areas.

The Romwe Catchment Study is unique in that an interdisciplinary approach is being taken. Moreover, work is being carried out with a catchment as the main unit for physical measurements and with a catchment as a focus for socioeconomic and institutional data collection. There are other catchment studies in Asia and Africa that have similar objectives as those of the Romwe Catchment Study; however in general, these studies are putting limited effort into collecting hydrological data. For example, the Ntshongweni Catchment Study in South Africa was set up in 1994 to develop a framework for community participation in catchment management, to assist local people in implementing ecologically and economically sound land use practices, and to help appropriate agencies to understand local people's current attitudes. Examples of catchment projects in India that have concentrated on social and institutional development are the Pidow Project in Karnataka State that started in 1986 (Pretty 1995) and the Indo-German Watershed Development Programme in Maharastra that started in 1989 (Farrington and Lobo 1997).

Model Classification

As figure 4 shows, mathematical hydrological models can be classified into two primary groups—deterministic and stochastic (Shaw 1988). Deterministic models are based on the assumption that hydrological events are governed by a fundamental set of hydrological processes that are subject to a unique set of initial and boundary conditions. Stochastic models, on the other hand, attempt to embody the unpredictability of nature by representing hydrological events as probability distributions. In this case, it is assumed that a *range* of events can arise from a unique set of initial conditions.

FIGURE 4.
Hierarchical classification of mathematical models.



Quoting Max Born, 'nature is ruled by laws of cause and laws of chance in a certain measure,' Ward and Robinson (1990) explain that there is essentially no conflict between these deterministic and stochastic approaches when applied appropriately. At the microscale all hydrological processes *may* be deterministic; however at larger scales the way in which the complex interactions of the microscale processes combine to determine macroscale behavior *may* not be predictable. When investigating ways of improving catchment water use deterministic models are most appropriate as we are primarily interested in the short-term effects on water resources of changing management practice. This cannot easily be predicted by stochastic models, which require long time series data to derive probability distributions.

As indicated in figure 4, deterministic models themselves can be divided into several sub-categories (Leavesley 1994). The characteristics of each of these model subtypes are outlined in table 2. As with any categorization, the boundaries suggested are not intended to be applied rigidly and it is recognized that a number of models may fall between two categories. The subcategories have been intentionally ordered to reflect increasing data requirements. In general, empirical models have the least-demanding input requirements (although large amounts of data may be required to develop the empirical relationships that are used) while distributed models will be the most demanding.

TABLE 2.
Characteristics of deterministic models.

Model type and examples	Description	Benefits	Drawbacks
Empirical *Calder* et al. *1995*	Outputs are inferred from statistical relationships derived between the outputs and selected inputs.	Simple; yet can provide good results depending on the quality of the relationship derived.	Catchment-and climate-dependent.
Water balance *Thornthwaite and Mather 1955; Gleick 1987*	Simple parameterizations expressing causal relationships between hydrological processes lead to direct estimation of average annual or monthly water balance components (usually stream flow).	Another simple approach providing a greater degree of process understanding	Requires calibration for individual catchment and climatic characteristics. Large temporal scale may lead to estimate inaccuracy.
Lumped *The IH lumped conceptual model (Eeles 1990), Sacramento Soil Moisture Accounting Model (Burnash, Ferral, and McGuire 1973)*	Physical processes are represented directly by sets of equations. Such a representation can only be approximate and often involves some degree of empiricism. Processes are usually represented at catchment scale.	Improved estimates provided by more detailed process simulation and higher temporal resolution. Potentially spatially transferable.	Increasing parameter and data requirements. Poor spatial resolution.
Semi-distributed *TOPMODEL (Beven and Kirkby 1979), Variable Infiltration Capacity Model (Wood, Lettenmaier, and Zartarian 1992)*	Similar to lumped models in that a physical approach is taken but spatial resolution is accounted for by using probability distributions of input parameters across the catchment.	All the advantages of lumped models but improved results might be expected due to the implicit representation of sub-model scale variability.	Potential difficulties in deriving input parameter distributions and in interpreting the results in practical situations. Not spatially specific.
Distributed *SHE (Abbott et al. 1986); IHC (Ragab, Cain, and Hough 1997)*	Similar to lumped models in that a physical approach is taken but with improved spatial resolution gained by dividing catchment into component areas.	Physical process representation with good spatial and temporal resolution. Spatially specific in that sub-catchment responses can be investigated.	Generally requires large amounts of (often unavailable) data for parameterization in each component area.
Hybrid	Makes use of one or more of the approaches discribed above.	The best techniques can be applied as appropriate.	Assumptions inherent to each approach may be inconsistent.

Model Utility

Generally speaking, models have two major functions (Beven 1989). First, they can be used to discern the nature of the physical processes operating in a system and, second, they can be used to make predictions concerning the future behavior of that system. If a model is to be used to make predictions then it should have already been assumed that it embodies a good understanding of the system behavior. In general, physically based models (as the name implies) are best suited to the first function while all sub-categories can, and have been, applied to the second (e.g., Robson, Whitehead, and Johnson 1993; Bathurst 1986; Arnell 1992; Eeles and Blackie 1993). It should also be noted that not all models will fulfill both of these functions; however, in the context of catchment water utilization, both uses are clearly relevant.

In the first case, it will clearly be of interest to derive an understanding of the interactions between water use at the top of the catchment and that at the bottom. To achieve this, models can be constructed that are based on initial assumptions made concerning the nature of these interactions and therefore expressing our understanding of the system. Comparing the behavior it predicts to that observed can then test the model. If the two agree closely then the assumptions on which the model is based can be accepted as a good description of the system interactions. If they do not, then further insight into the nature of the interactions will be gained, enabling the model to be suitably adapted and tested again.

The advantages to be gained from successful prediction are obvious. Great efforts are currently being exerted to evaluate land use and management changes arising from policy decisions (e.g., Veldkamp and Frescoe 1996; Fischer et al. 1996; Turner et al. 1995). Currently such efforts have largely been concentrated at scales larger than the catchment; however, it is clear that this sort of information could be of equal benefit at the scale of the catchment itself. Further value can be obtained by extending this application so that the effects of land use change on catchment water resources can be quantified.

In spite of this great utility, models should always be applied carefully and their results interpreted critically. To quote Woolhiser and Brakensiek 1982:

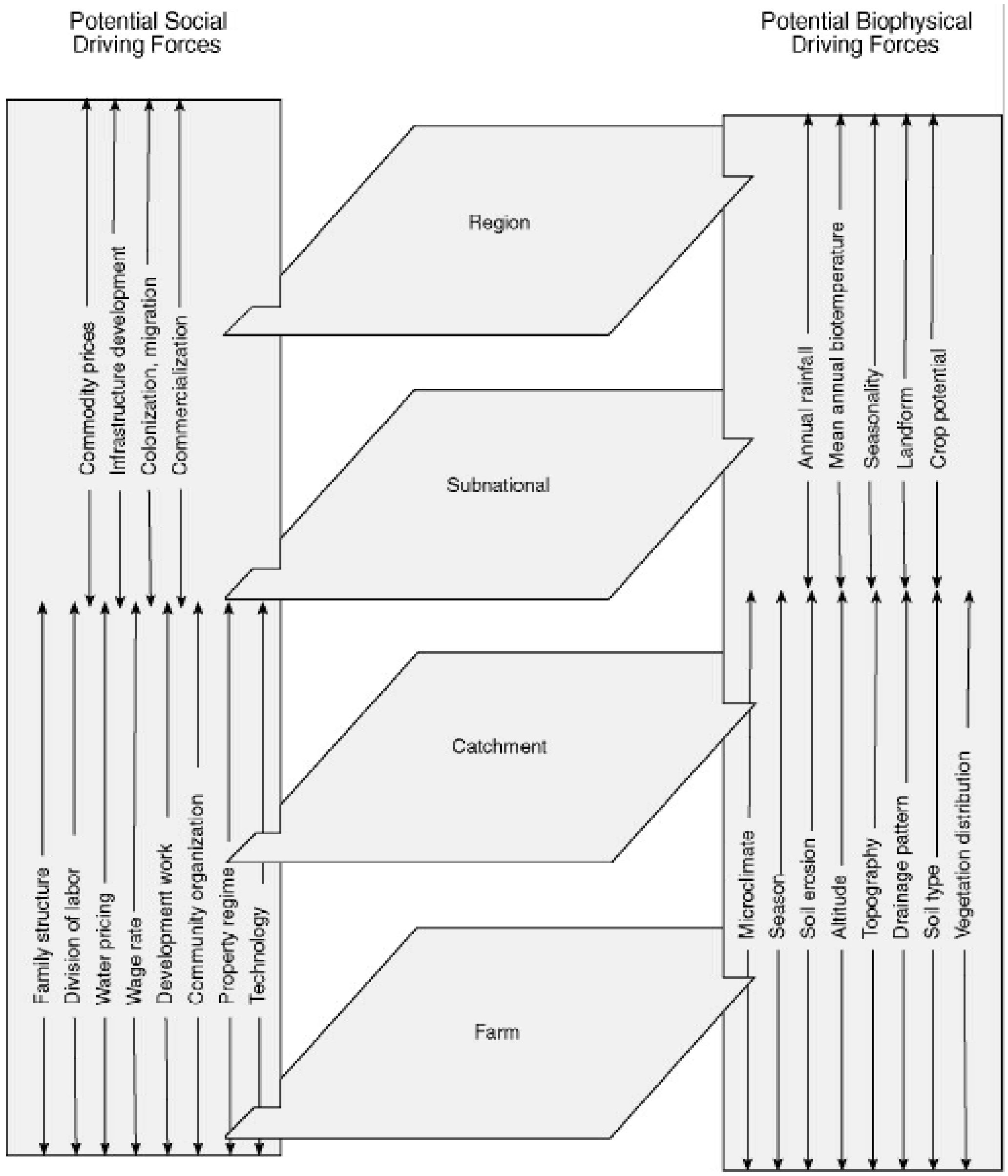
> *All theoretical models simplify the physical system and are, therefore, more or less incorrect. In addition, the so-called theoretical models often include obviously empirical components. All empirical relationships have some chance of being fortuitous; that is, by chance two variables may appear to be correlated when in fact they are not.*

When used correctly and with care, however, models can provide benefits that would otherwise be unobtainable and are therefore extremely useful tools in understanding the behavior of natural processes.

Model Scale

As it is practically impossible to simulate all the physical processes active in a hydrological system (even if we could identify them all), a model should aim to identify and simulate the most important ones. The key processes, however, vary depending on the scale of the system being considered (Bloschl and Sivapalan 1995; see also figure 5). For example, at a small scale, runoff generation may largely depend on local soil moisture conditions and vegetation cover whilst, at a larger scale, topography may become more important. Runoff generated at one point may infiltrate into the soil at another only a short distance away where the soil surface is drier and if this were to occur across an entire hill slope then the net runoff would be zero. It can be seen, therefore, that at larger scales physical processes tend to express some sort of average of the processes dominant at smaller scales.

FIGURE 5.
The scale dependency of key processes.



It follows, therefore, that as key processes change with scale, so should the models which attempt to simulate them. Most physically based models describe processes at the microscopic scale where, as discussed earlier, behavior is relatively deterministic. To retain this physical approach, methods are generally sought that will enable these small-scale descriptions to be applied effectively at larger scales (the alternative would be to develop models based explicitly on large-scale processes which, having a large degree of uncertainty associated with them, would tend to be less deterministic and more stochastic in nature). This can be defined as the scaling problem (Beven 1995). The report on the IGBP workshop held in Sweden in 1990 (IGBP 1991) gives characteristic spatial and temporal scales for a range of key processes active in semiarid systems (table 3).

TABLE 3.
Characteristic spatial and temporal process scales in semiarid systems (after IGBP 1991).

Process	Spatial scale	Time to understand process (years)	Importance
Hydrology			
Groundwater recharge	1, 2,3	5	*
Channel flow	1,2	2	**
Runoff generation	1,2	15	**
Horizontal soil water movement	1	2	*
Water balance processes	1,2,3	20–50	***
Rainfall	1,2,3	20–50	***
Soils			
Soil erosion	1,2	1–5	**
Salinization	1,2,5	5	***
Soil degradation	1,2,3	20	***
Vegetation / Ecosystems			
Carbon dioxide enrichment	1	5	***
Plant competitive interactions	1	10	***
Plant growth	2,3	2	**
Carbon allocation	1	5–10	*
Fire	1,2,3	20–50	***
Other			
Human interactions	1,2,3	30–50	***

Spatial scale codes

1. Patch (to 1 km x 1 km)
2. Small mesoscale (to 10 km x 10 km)
3. Intermediate mesoscale (to 100 km x 100 km)

Importance codes

* Desired
** Necessary
*** Urgent

Time to Understand Process

The times given reflect the length of time to develop a better understanding and also the time length of the data set. Thus water balance processes require a data set of 20–50 years but understanding can be gained within 7 years. Research on many of these problems may require transects or multiple research sites. Aside from the change in key processes, a major problem in doing this arises from heterogeneity of physical properties. The larger the scale being considered, the more any particular physical property being considered will vary across it (this is equally true for both spatial and temporal scales). A theoretically simple approach involves deriving effective parameters. These are parameters which, when used in small-scale models applied to larger scales, provide the same answer as would be expected if the small-scale models were applied to small scales with each of the values that parameter might vary across and the results aggregated.

Due to the nonlinear behavior of most physical processes, however, this is far from simple in practice. As an example, evaporation is often predicted in hydrological models using the Penman-Monteith formula (see Monteith and Unsworth 1990). A parameter in this formula expresses the resistance to water vapor transfer from the canopy surface to the atmosphere. This parameter is known as the canopy resistance and it varies widely for different vegetation. Due to its nonlinear nature, however, if the formula is to be applied to estimate the evaporation from two fields of different vegetation then the answer given by the formula using an average of the two canopy resistances (an effective parameter) will not be the same as an average of the answers given by applying each formula separately to each field. In spite of its difficulties, however, this approach is characteristic of lumped models.

A second approach defines statistical distributions that represent the variation in a particular parameter across the area (or time) being considered (for example, soil infiltration capacity). This is possible if is assumed that, at a particular scale, the arrangement of the heterogeneity ceases to be important so allowing the distribution alone to be used. Wood et al. (1988), among others, have identified such scales that they term Representative Elementary Areas or REAs (see also Wood 1995). This approach is characteristic of semi-distributed models.

A third approach divides the area to be considered into subunits, applies small-scale models to each subunit individually, and aggregates the model outputs in some way to give an estimate for the entire area. The subunits can be defined as simple grid squares or as areas that are identified as being hydrologically similar in some way. This is known as the distributed approach.

Problems arise with the calibration and validation of all these approaches and this will be discussed in the next section.

Calibration, Testing, and Data Requirements

Calibration is the process of selecting and tuning the parameters in a model so that the model performs to its optimum capacity as judged by validating the model against measured data. The way in which this is done is dependent on the type of model being dealt with. For empirical and water balance models, parameter adjustment will generally be guided by the fit between the model output and the observed behavior (as judged by some objective function). For physically based models, however, parameters are chosen to represent some sort of physical reality and are therefore constrained in the values they take (a surface infiltration rate of 1,000 m of water every second is clearly unrealistic and would not be accepted in a physically based model, no matter how good the results it might produce). Such constraints can often prove problematic, especially when there is minimal information about the range of values a parameter might take in the environment under consideration.

Calibration raises a number of practical and conceptual difficulties for all model types. For simple empirical models, which are intended for use only in the conditions for which they are calibrated, these difficulties will largely arise as a result of insufficient historical data with which to derive a satisfactory correlation. However, more complicated models will suffer from parameter intercorrelations that can mask model and data errors (Leavesley 1994). Underestimation in one parameter may be compensated for by overestimation in another, resulting in the right answer for the wrong reason. This may be more acceptable in simple models where the right answer is more important than the right reason but such an eventuality undermines the entire conceptual basis of physical models.

One approach that can be used to gain an acceptable model fit involves increasing the number of parameters whose subsequent adjustment may lead to better results. Jakeman and Hornberger (1993) argued that the quality and detail of the available data rarely justify doing this. Analyzing model performance, they found that for temperate catchments a permissible model complexity is in the region of four parameters. Moreover, Hornberger, Dlamimi, and Biftu (1985) and Loague and Freeze (1985) found that more complex models performed less well than simple ones while Yew Gan, Dlamini, and Biftu (1997) showed that model performance is more dependent on model structure, choice of objective function, and data quality than on model complexity. If improved performance is achieved, however, it is just as likely to result from parameter intercorrelation than from any improvement in the representation of the physical processes. Indeed, Beven and Quinn (1994) showed that a wide range of parameter sets can be fitted so that models are able to reproduce observed data.

Further problems arise when attempting to derive single physically based parameters that aim to represent the aggregated behavior produced by the variation in a particular physical property in either space or time. This is generally only thought to be a problem for lumped models; however, Beven (1989) convincingly argues that distributed models are equally at fault in this respect due to the heterogeneity present within the grid squares. Semi-distributed models neatly avoid this by defining the variation as a statistical distribution; however, the accuracy to which this distribution represents reality will depend on the amount of data available to derive it.

Heterogeneity also presents a problem for model validation. With the notable exception of discharge data, most other measurements represent a physical property at a single point in space and time. Models aim to produce an output, which represents the combined results of processes. These processes are controlled by physical properties, which vary across the area or time frame being considered. For example, the UK Meteorological Office MORCES (Hough et al. 1996) model produces estimates of soil moisture and evaporation (among other things) for a series of 40 km grid squares across the UK. It then makes little sense to compare this output to measurements that arise from processes that are controlled by a single set of physical properties at a single point. As a possible solution to this problem of scale, Schmugge and Jackson (1996) have shown that taking a simple mean of soil moisture values measured over an area provides an acceptable single value to represent the variable soil moisture. This technique, however, clearly requires a large number of measurements across the area being considered that may be impractical. Techniques, such as remote sensing, that measure values aggregated over large areas (e.g., Pelgrum and Bastiaanssen 1996; Lagouarde, McAneney, and Green 1996) may overcome this problem in the future (spatially, at least), but much work remains to be done if this problem is to be adequately addressed (IGBP 1991).

Even leaving aside issues of parameter variability, validating a model is far from simple. Quantitative measures must be defined that can establish the adequacy of model performance when compared to measured data. Statistical techniques exist for doing this (Mead 1983) but the problem is complicated when the model is intended for general application in a variety of different environments. As model transferability is desirable this problem must be solved. Klemes (1986) proposes two tests that are designed specifically for models whose outputs will be used in a predictive capacity to make planning decisions. With reference to models, which facilitate catchment water management, the first test would calibrate the model using data from a wet period and then validate the model during a dry period (and vice versa). The second test would be similarly applied to two catchments in the same region, calibrating the model with a dry period from one catchment and validating it with a wet period from the other. Data presented by Yew Gan, Dlamini, and Biftu (1997) suggest that wet years allow better calibration than dry years as the former contain more hydrological information.

Even if a model fulfilled these demanding criteria some uncertainty in model predictions would naturally remain. Beven and Binley (1992) propose a methodology that enables estimations of uncertainty to be attached to model outputs when being used in a predictive capacity. This approach has the advantage of explicitly recognizing that outputs produced by deterministic models are only estimates and not certainties, an important consideration when using models for water resource planning.

As Hillel (1991) concludes, we cannot view models in isolation but must judge them in relation to the data available to calibrate, validate, and run them. To quote Hillel:

> *Ask not the computer simulation alone, for it may portray a make-believe world. Ask nature itself, too…*

Unfortunately, sufficient data are rarely available to provide nature's answer and this presents a major limitation on our ability to develop and parameterize models (Leavesley 1994). Consensus suggests that further progress requires models to be developed in conjunction with data collection programs that are specifically designed for this purpose.

Linking Physical and Economic Models

Catchment water resources are determined by the hydrology of the catchment, which, in turn, is influenced by the land use and cover. To a large extent, the land use of an agricultural catchment is a result of some human decision-making process, be it at the farm, regional, or national level. While a wide range of sociological and psychological factors influences these human decisions, it can be argued that their prime rationale is often economic.

If catchment hydrology is dependent on land use, it is equally true that land use is constrained by the available water resources. It is therefore important to be aware of the potential impacts on the hydrology of a catchment when formulating a particular land use policy. Recently, significant research effort has focused on predicting land use change in response to economic stimuli (e.g., Audsley, Sells, and Sandars 1996; Rehman, Tranter, and Jones 1996) and such predictions can be extended through linkages with hydrological models to estimate the likely effect in water resources. This information can then be fed back into the decision-making process and ultimately contribute to a better and more effective environmental policy. Several attempts have already been made to do this (e.g., O'Callaghan 1995; Hoekstra 1995). In some cases, detailed output is sacrificed to achieve generality whilst in others the output gives no real understanding of how the system is interacting as a whole. These problems are not trivial and must be tackled if integrated modeling is to become a fully effective tool.

The ultimate objective is to produce a model capable of simulating all the important dynamics of a system so that the system can be truly understood. It is unlikely that traditional deterministic modeling techniques alone will provide the flexibility required to analyze physical and socioeconomic dynamics as an integrated system. Instead, a framework should be created within which deterministic models might interact with economic evaluation techniques, decision-making methodologies and statistical analyses. Such a framework must enable multi-scalar analysis, deal with qualitative data in a sensible way, and allow uncertainties in model predictions to be quantified and incorporated in subsequent analyses. Ideally, it should facilitate the involvement of all those stakeholders who may be affected by any management decisions based on the model's output. For example, the model could be designed to communicate in a non-specialist way the means by which it arrived at its output. Additionally, the framework might *enforce* user involvement as one of its analytical components. For example, output from a mathematical model could be accepted only after validation based on stakeholder perception.

The basis for such a framework might be provided by a Bayesian Belief Network (see Jensen 1996; Spiegelhalter et al. 1993). These networks offer a method of representing relationships between different factors even though that relationship might be uncertain or ill-defined. Therefore, they provide a powerful tool by which the relationships between socioeconomic and physical dynamics can be identified and investigated. This is facilitated by the network's potential to analyze deterministic model outputs in the same structure as statistical survey data or even qualitative judgments. They not only capture knowledge in a way that is easy to understand but are also capable of supporting optimal decision making based on stakeholder values.

River Basin Modeling

When discussing catchment management, it is important to note that a catchment does not function in isolation but as part of a larger system. If efficient or productive use of water is to be achieved at a catchment scale, then it is important that this is supported and complemented by the management of the river basin in which it may sit. This section will discuss approaches to effective management of large river basins. By large river basins, we mean those with catchment areas of from tens of thousands to over a million square kilometers.

Many river basins now accommodate a multitude of engineering schemes that manipulate the river for a wide range of different purposes. For example, a system might typically include combinations of multipurpose reservoirs for domestic, industrial, and irrigation supply, as well as for hydroelectric power generation, flood control measures, groundwater abstraction schemes, works concerned with effluent returns, and possibly interbasin water transfers. For both the planning of new developments and the improved operation of existing schemes, it is necessary to study the effects of each current or proposed system component on the river basin as a whole. This integrated, basin-wide approach is becoming recognized, and accepted, as the only effective way forward (United Nations 1988; Loucks 1994), and there is a growing need for powerful, flexible models that permit the study of the water resources of a whole river basin.

For large river basins it may be necessary to model the system at a somewhat coarser scale than those described previously, not only so the large number of physical features within the basin can be handled, but also to diminish the problems of collecting the appropriate data. The range of attributes to be modeled will generally be both natural (transmission losses within the river systems, natural lakes, wetlands, and groundwater recharge) and man-made (dams, irrigation schemes, river abstractions and returns, and possibly interbasin transfers). Models may require daily data, but where large reservoir or lake storage is available, it may often be possible to use a weekly, 10-day, or monthly time steps.

At this scale, the aim must be to model each individual feature with sufficient accuracy so as to ensure that the overall water balance is correct for the entire basin. This allows individual features to be modeled in a way that may not be truly physically representative. As an example, where a groundwater abstraction scheme is being modeled at the basin scale, it is neither necessary nor feasible to consider the behavior of individual boreholes. It would suffice to have a good understanding of the physical characteristics of the entire aquifer and borehole group so that a physically based aquifer model can be run. The aim in doing this is to represent the aquifer and borehole group in the water resources model by a simple inflow/outflow/storage function. In this way, account may be taken of aquifer storage during the simulation period, and any periods of failure to meet demand.

Early work on such water resources simulation models was undertaken at Harvard University (Mass et al. 1962; or Hufschmidt and Fiering 1965) and a range of models evolved during the 1970s and 1980s that aimed to simulate the behavior of complex river basins (e.g., Austin 1986; OTA 1982). In direct simulations, the basin is represented by a series of nodes and links, where a node may be a river flow gauging station, a reservoir, an offtake or return, a pump, or any other point feature. Links represent rivers, canals, pipelines, or aqueducts of some sort. The network model is run repeatedly for a range of possible operating rules and configurations to find the solution that best meets the imposed criteria. Simulations are on a 'trial and error' basis and there is no automated procedure for finding the overall optimum solution. However, compared to more formal techniques, simulation has the advantages of requiring fewer modeling simplifications, of avoiding the need to formulate idealized objective functions, and of being easier for practitioners to understand.

For planning studies, various time series may be used in the simulation approach. In UK practice, it is common to use either the observed historical flows or a synthetic sequence representing a drought with a known return period and duration (typically up to a few years). Although 'one shot' approaches such as these are widely used, the disadvantage is that only one possible flow scenario is considered with the certainty that, whatever the future holds, past events will not be repeated exactly. In some countries, this has led to the use of stochastically generated sequences to explore a wider range of possible future conditions.

Such methods are particularly used in semiarid regions, such as South Africa and parts of the USA, where, due to the large interannual variations in flows and persistence of high- and low-flow periods, assessments based on short runs of observed data alone are often of limited value. Also, storage volumes are often large compared to the mean annual flow volume, allowing the analysis to be performed using monthly or annual time steps, which are typically the only meaningful time steps on which stochastic models can be used. A simpler but less-comprehensive approach is to 'wrap around' the observed series so that multiple series are generated, each starting from a different year in the observed record. Alternatively, if there is no significant serial correlation, multiple series of annual data can be generated by random sampling from the observed records.

The aim of all these approaches is to explore the response of the river basin system to a wide range of plausible future flow scenarios, including drought sequences that are more severe than the worst on record (although with a lower probability of occurrence). The output produced is in the form of a probability distribution for each of the parameters of interest (system yield or rate of failure, for example), from which statistical measures (such as mean values and the uncertainty probabilities for these values) can be extracted. Cost and penalty functions may also be included to give probabilistic estimates of system operating costs. McKenzie and Allen (1990) give several good practical examples of ways of using and interpreting the output from stochastic simulation methods of water resources systems.

Improving Efficiency of Water Utilization at the Catchment Scale

Integrated Catchment Management

In most semiarid areas, there is limited scope for increasing the available water resources by constructing large civil engineering works. This is because the water resources have already been developed or because the high social, environmental, and political costs of large civil engineering works have reduced the willingness of governments and agencies to commit the large amounts of funding needed. There are, of course, a few notable exceptions such as the Narmada and Three Gorges Dams. In many semiarid areas there is considerable scope for developing additional water resources by constructing small dams or by using innovative techniques to develop groundwater resources. One such tech-nique or approach that has been used very successfully in southern Africa involves the development of collector wells in crystalline basement areas as a source of water garden or allotment-scale irrigation (Lovell et al. 1996). A collector well is a shallow hand-dug well of large diameter (2–5 m) with horizontal boreholes drilled radially from the base to a distance of approximately 30 m, typically in four directions.

Notwithstanding the potential for increasing, in particular, the development of groundwater resources in many semiarid areas, increasing demand and competition for water resources have emphasized the need for improvements in the management and efficiency of water utilization at the catchment scale. Many institutions and international agencies are showing considerable interest in integrated catchment management (ICM) as a practical means of improving the management of water resources, reducing environmental degradation, and promoting sustainable agricultural development. ICM programs that are having some success comprise the following components:

- an overall natural resource management strategy that clearly defines the management objectives
- a range of delivery mechanisms that enable these objectives to be achieved
- a monitoring schedule that evaluates program performance

ICM programs are based on the principles that:

- Decision making and action take place at the lowest appropriate level whether it be at the farm, village, catchment, or district level. Wherever possible, stakeholders are involved both in decision making and in the resulting activities (at the local level, stakeholders include farmers, community groups, and local institutions, while at the national level, they include a number of different government departments and agencies, farmer organizations, and NGOs).
- Delivery mechanisms and enabling policies are established that provide long-term support to programs of environmental recovery and sustainable development. This may not be attractive to bureaucrats and politicians who want a quick fix or another glittering initiative. It is nevertheless a fundamental requirement.
- Rural development is considered to be process-oriented rather than target-oriented.

Implementing Community-Based ICM

To date, a failing of many ICM strategies has been that, while they have been able to articulate the right aspirations for the management of resources, they have not been able to bring about improvements in resource management at the catchment scale (Blackmore 1994; van Zyl 1995). One of the main reasons for this has been the lack of delivery mechanisms that generate the interest, and prompt the participation of local institutions and communities. The delivery mechanisms that have met with relative success in Australia involve the use of financial incentives. It is a simple fact that few countries in semiarid areas have the same political will and financial resources as Australia. Hence, the need to identify approaches to implement ICM appropriate to the political settings in Africa and Asia, at the same time as being considerably cheaper than the ICM programs being implemented in Australia. Although it is too early to be totally confident, there is evidence that a first community-based water project such as the implementation of a *productive water point* can provide the delivery mechanism or initial step that brings about a reversal of the feedback loops described in figure 2. The evidence, based on experience from southern Zimbabwe (Lovell et al. 1996; Waughray et al. 1997), is as follows:

- Unlike many improved resource management practices, productive water points produce a range of benefits to a large number of community members in a short space of time. The immediacy of these benefits is crucial because it provides the incentive for communities to overcome leadership or other social problems that are almost inevitable with community-based projects.

- Having successfully implemented a scheme and started to benefit from it, communities become aware of the need to protect this scheme by managing the recharge zone around the water point. In some cases, this intrinsic awareness needs to be reinforced by external agents such as extension workers.

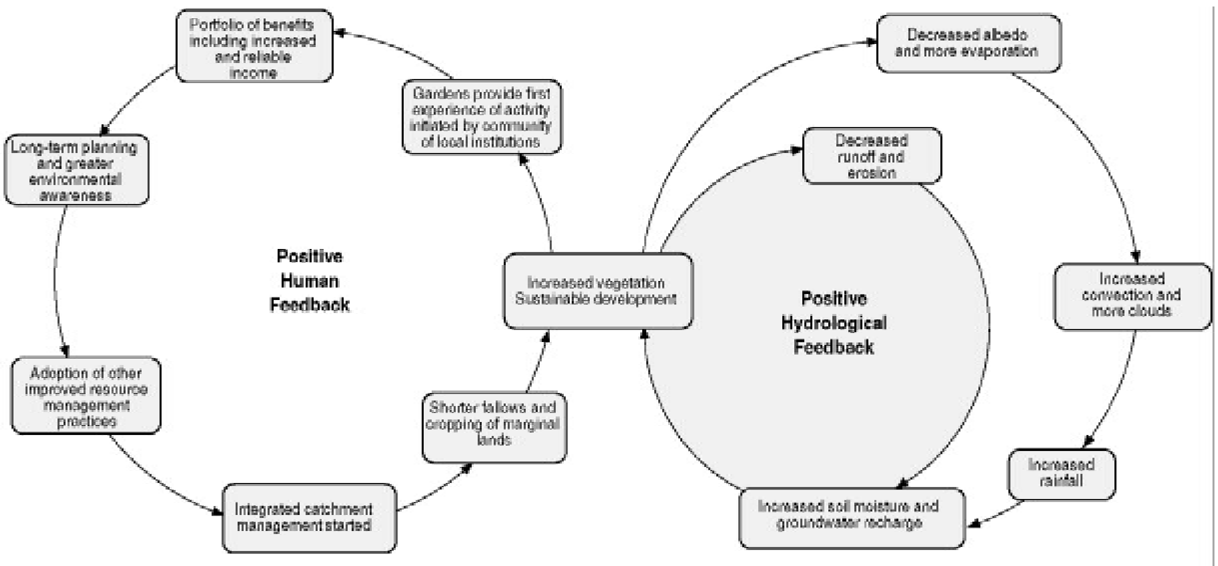
- Experience and social capital gained from a first community-based productive water point can be used to establish other improved resources management practices. It is also clear that confidence gained from implementing a first scheme inspires communities to tackle other natural resources problems either by themselves or with the help of external agencies. Ideally, communities, working with appropriate assistance, will develop their own natural resources management strategy and start a program of integrated catchment management. In some cases, this natural resources management strategy might be developed prior to the establishment of a community garden as part of a consultative village inventory or participatory rural appraisal exercise.

- Productive water points enable income to be generated by individuals and by relevant committees. Lack of income is a huge impediment to entrepreneurial activity. Revolving or community funds can be used to initiate a range of activities, some related to agriculture and others to commerce or cottage industries.

- Productive water points provide a regular meeting place for informal discussion and problem-solving. Women working in the garden and pumping and collecting water are able to discuss and plan either proposals emanating from within the community or from outside agencies.

Although the sequence of steps may vary, figure 6 is an attempt to show that a first community garden and public water point could lead to improved resources management practices that will lead to increased vegetation cover at a village and catchment scale which, in turn, will lead to a reversal of the physical feedback. However, the reversal of this feedback will not be straightforward if climate change has occurred due to external factors. Similarly, if the human feedback is being strongly influenced by external factors (e.g., economic structural adjustment programs) then reversal may not be possible. The Romwe Catchment Study, which was described earlier in this paper, is currently evaluating the hypothesis that community-based productive water points can perform an important role in implementing ICM.

FIGURE 6.
Positive feedback mechanisms that lead to restoration of degradation.



Van Zyl (1995) emphasized that for ICM to succeed it must be people-centered and environmentally focused. Van Zyl (1995) also stated that:

> *To succeed in managing…managers must be in a position to see the whole picture, understand the resources, the customers, their needs and aspirations, and to make wise decisions in the interests of all. This requires a holistic approach to management which integrates skills in engineering, economics, politics, and social and environmental management. It involves the bringing together of various disciplines and the compilation and development of multidisciplinary teams of champions. Due to the unique site-specific nature of water resources in terms of physical properties, specific land-use and people involved, it is not feasible to manage the country's (South Africa) water resources on a national basis without basing it on logical management units. Because we are dealing with a natural resource, driven by the hydrological cycle, it makes good sense to use river catchments as such units.*

This is ICM as viewed from the top whereby regulation and equitable distribution between water users are given high priority. Whilst this approach has many benefits, the crucial element that is often missing is the local "ownership" for any natural resources management strategies that might be developed as part of the ICM. An alternative view of ICM is from the bottom whereby ICM is seen as a means of scaling community-based schemes to the catchment scale. Whilst this approach has advantages in terms of achieving local "ownership," it can have disadvantages with regard to regulation and equitability. For example, communities developing projects in headwater catchments are unlikely to put high priority on ensuring that water resources of downstream users are not adversely affected by these projects. Farrington and Lobo (1997) identify some of the policy preconditions needed to overcome the dichotomy of ensuring local "ownership" at the same time as ensuring equitable distribution and regulation of water resources at the catchment scale. These are:

- The close engagement of stakeholders, and marshaling of political support, at international, national, state, and subsequently district and local levels, and the creation of confluences of interest (and corresponding checks and balances) with and between levels.

- The creation of a local watershed planning methodology that is technically defensible to funding agencies and is yet participatory and accessible to community-based organizations (CBOs); the provision of appropriate capacity-building and technical support to these.

- The existence of a framework for local-level collaboration among NGOs, CBOs, and government departments, including setting of preconditions for NGOs and CBOs to join the Program.

- The creation of mechanisms that channel funds to local organizations with as few intermediate stages as possible; some authority by these to contract in-services, especially training.

- The existence of a mechanism for promoting the approach across major political and administrative boundaries.

The basic problems of reconciling top-down and bottom-up views of managing water resources are also discussed by Bottrall (1992) who makes the point that government departments address issues on a fragmented sectoral basis. Attempts by government departments to promote ICM tend to have high administrative costs (interdepartmental coordinating committees or a new multi-sectoral unit). By contrast, farmers find it relatively easy to think and act holistically. It may be possible, therefore, to keep the administrative costs of ICM within acceptable limits by delegating a large part of local management responsibilities to farmers' organizations and, wherever possible, to NGO intermediaries.

Catchment Water Use Efficiency

When considering water use efficiency at the catchment (or larger) scale we need to take account of the interactions between different units in the landscape as well as the different water users. It is also important to distinguish between "real" and "paper" water savings (Seckler 1996). A holistic vision should be to consider the efficiency or productivity with which water is used at different places in a catchment by different users and the degree to which different uses degrade the water quality. Ultimately, catchment water use efficiencies should be calculated (and optimized) not only in physical terms but also in economic, social, and environmental terms (Wallace and Batchelor 1997). Seckler (1996) suggests that opportunities for improving catchment water use efficiency lie in four directions:

- increasing output per unit of evaporated water

- reducing losses of usable water to sinks

- reducing water pollution

- reallocating water from lower-valued to higher-valued uses

Another direction that could be added to this list is maximizing the recycling of evaporated water within large catchments. Recycling of moisture by vegetation across continents and within large catchments is an important process (Savenije 1994). Shuttleworth (1988) suggested that half the rainfall in the Amazon basin originated from forest evaporation and not evaporation from the oceans. With regard to irrigation, current theory suggests that irrigation during the dry season implies a loss of recycling capacity (or loss of water to the atmospheric sink), as water evaporated during the dry season does not enhance rainfall.

Improving Efficiency of Water Utilization at the Sub-Catchment Scale

Scope for Improving Efficiency of Water Utilization at the Sub-Catchment Level

There is considerable scope for improving the efficiency of water utilization at the field scale, since in both rain-fed and irrigated agriculture only about one third of the available water (as rainfall, surface water, or groundwater) is used to grow useful plants (Wallace and Batchelor 1997). Wallace and Batchelor (1997) also discuss the main options available for improving crop water use efficiency at the field and farm levels.

Uptake of Technologies that Improve Water Use Efficiency

Numerous environmentally benign technologies have been shown to have the potential to improve agricultural sustainability, production levels, and efficiency of water utilization in semiarid areas. These include contour farming to reduce runoff and soil erosion, mulching, minimum tillage, crop mixtures and rotations that ensure continuous soil cover, terracing and bunding, integration of livestock and arable cropping to maintain soil fertility, agro-forestry, integrated pest management, and water harvesting (Cleaver and Schreiber 1994; Reij, Scoones, and Toulmin 1996). It should be noted that many of these technologies have been known and practiced in certain areas for millennia. This being the case, it has to be asked why it is that the adoption of these technologies is not more widespread. To researchers, politicians and, resources "managers," it seems obvious that farmers should adopt these technologies. However, the perceptions of farmers are usually very different and very dependent on the physical, social, economic, and institutional circumstances in which they operate.

Key reasons for non-adoption of these technologies appear to be the facts that farmers have not demanded them, that there is often a poor fit between the technologies and resources available to farmers, and that, in many cases, the technologies lead to increased risks, at least in the short term (Cleaver and Schreiber 1994). A recent review of technologies acceptable to resource-poor farmers points out that combining practices into a farming system must take account not only of the physical factors such as soil type, slope, and climate, but equally the available resource inputs, especially cash and labor, and the farmer's objectives (Stocking 1993). The objectives of the commercial farmer are usually to maximize yield and income, but the subsistence farmer is likely to be more interested in improving food security by reducing risk of crop failure, or improving the return on inputs of seed, fertilizer, and labor, or improving the quality of life by reducing drudgery, particularly in the case of women farmers (Hudson 1995).

In the last few years, there has been an increasing volume of research that has questioned the general view of most policy makers that soil erosion and environmental degradation are major problems in dryland areas of Africa (e.g., Tiffen, Mortimore, and Gichuki 1994; Leach and Mearns 1996). This research puts emphasis upon Boserupian processes of agricultural intensification as opposed to the pessimism that has previously prevailed in many studies of African peoples, their livelihoods, and their environment (Murton 1997). The often-quoted study by Tiffen, Mortimore, and Gichuki (1994) suggested that, from the 1960s, a major transformation of the farming landscape took place with huge voluntary investment in conservation works resulting in falling erosion rates, increased environmental rehabilitation, and a boost for agricultural productivity. The reasons identified included: increasing population densities and the resultant land scarcity combined with improved access to the growing market of Nairobi. Other reasons were the access to information through informal networks, as well as formal extension advice, that enabled farmers to try out a range of conservation measures. Murton (1997) presents findings of research in the Machakos region of Kenya, the location of the study carried out by Tiffen, Mortimore, and Gichuki (1994). These findings confirmed some of the earlier findings with regard to environmental transformation and the adoption of soil and water conservation measures. However, Murton (1997) suggests that the earlier findings do not tell the whole story. Although agricultural production per capita may have risen over the district as a whole, this is not true for all people or all places.

Another example of population pressure contributing to agricultural intensification can be seen on the Jos Plateau in Nigeria (Cleaver and Schreiber 1994). The Kofyar people initially lived as subsistence farmers on the Jos Plateau. As population density on the escarpment increased, farming systems were intensified with increasing reliance on agroforestry, terracing, and manuring. When population pressure on the plateau outpaced the ability of the farming system to sustain the increased numbers, the Kofyar obtained permission from tribes in the Benue river plains to clear lowland forest and farm there. The migrants abandoned the intensive farming techniques they had practiced on the plateau and adopted instead an extensive forest-fallow farming system focused on cash cropping and market-oriented animal production. Cleaver and Schreiber (1994) suggest that it should not be surprising that this process is observed in certain areas of developing and developed countries. If there is no land constraint, and if land is free or very cheap, it makes sense from the farmer's perspective to extend the use of land and minimize the use of other inputs including capital and labor. If, however, land becomes scarcer, there is an obvious incentive for individual farmers to intensify agricultural production and to take better care of the limited land available to them.

Unfortunately, the intensification process observed in Machakos and on the Jos Plateau is not seen throughout sub-Saharan Africa. In fact, sluggish agricultural growth and severe environmental degradation are the norm throughout the region.

Cleaver and Schreiber (1994) hypothesize that, in most of sub-Saharan Africa, the rapidly increasing population over the last 20 to 30 years has overwhelmed the only slowly evolving rural traditions of farming, livestock production, fuelwood provision, land allocation and utilization, and gender-specific responsibilities in household maintenance and rural production systems. This has led to and accelerated degradation of natural resources that, in turn, has contributed to a low rate of agricultural growth. In short, a range of complex interlinked factors has prevented agricultural intensification taking place and, as a consequence, natural resources are being depleted.

Although the policies of governments or other financing organizations alone will not lead to the uptake of water-efficient technologies, policies can play an important role in encouraging the uptake of improved technologies or practices. Using 20 detailed case studies and field- and community-level data from more than 50 projects, Pretty (1995) identifies some of the common elements needed in the successful implementation of sustainable agricultural practices. He also states that *the major new challenge lies in the development of new approaches to policy formulation. The problem with traditional policy making is that it is appropriate only for non-complex systems. For a more sustainable agriculture to succeed, policy formulation must not repeat the past mistakes of coercion and control. Rather, it will have to find ways of being enabling to creating the conditions for sustainable development based more on local resources, skills and knowledge.*

Concluding Remarks

Catchment Studies

There is a fundamental need for long-term catchment studies that relate to improving the management of water and other natural resources, reducing environmental degradation, and promoting sustainable development. It is, therefore, highly desirable that SWIM identify and instrument a number of small catchments representative of a range of physical, socioeconomic, and institutional settings. These catchments should be used for hydrological, agricultural, and forestry research and as a focus for social development, institutional development, and economic research. Implementing productive water points as a means of engendering the active participation of local communities and institutions should be considered. The Romwe Catchment Study in Zimbabwe provides a good model for interdisciplinary catchment studies that involve local communities and institutions in data collection and analysis.

Catchment Modeling

There are a large number of hydrological models that have been developed for a wide range of purposes. Many of these could be used by SWIM. However, the development of combined hydrological, agricultural, and socioeconomic models (CHASM) is particularly relevant to SWIM. It is recommended, therefore, that data collection and the establishment of a SWIM be carried out in conjunction with the development of CHASM models. The potential for incorporating Bayesian Belief Networks into CHASM models should be investigated.

Integrated Catchment Management (ICM)

There is considerable interest in ICM in many parts of Africa and Asia. Despite the problems encountered during early attempts to implement ICM, integrated management still makes sense and is the only sensible option in many dryland areas of Africa and Asia. Research effort is required to identify ICM delivery mechanisms that are appropriate to Africa and Asia. Research effort is also required on reconciling top-down and bottom-up approaches to ICM and on identifying the driving forces that determine decision making at different levels.

Improving Efficiency of Water Utilization at the Catchment Scale

The need for improved efficiency of water utilization is echoed time and again worldwide. Research effort is required:

- To distinguish more clearly between "real" and "paper" losses of water at the catchment scale and to define and evaluate appropriate measures of catchment water use efficiency that can be used when monitoring or optimizing water use efficiency at the catchment scale.
- To provide a better understanding of the recycling of rainfall within large catchments.
- To evaluate innovative methods of developing groundwater resources. Horizontal drilling techniques have been shown to have enormous potential for developing additional water resources in crystalline basement areas.
- To develop and assess innovative methods of establishing collective responsibility for water resources.

Improving Efficiency of Water Utilization at the Sub-Catchment Scale

Despite the research effort that has been directed at developing and evaluating technologies that can lead to improved water use efficiency at the field and farm levels, there is still much to be learnt as part of participative catchment studies. Research that could be carried out as part of SWIM includes:

- Assessing the impact of a range of research recommendations individually and as part of wider farming and livelihood systems.
- Assessing the long-term viability and sustainability of a range of research recommendations in physical, socio-economic, and environmental terms.

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