TOWARDS DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR WATER RESOURCE DEVELOPMENT IN SEMI-ARID MICRO-CATCHMENTS

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Towards development of a decision support system for water resource development in semi-arid micro-catchments

Patrick Barré Moriarty[2]

Abstract

The objective of the paper is to bring together, within a single holistic framework, the principle findings of the research into the physical and human aspects a study in Romwe micro-catchment in southern Zimbabwe. The framework is developed using Bayesian Belief Networks (BBNs) to identify and model the central aspects of both physical and human environment (at both the micro and macro scale), and their impacts on each other. In particular I look at the likely impact of effective catchment management (here taken to be physical and technical interventions) on the probability of livelihoods improving. BBNs offer an exciting new way of bringing together very disparate data sources within useful frameworks, which could then be used not only for decision making about development needs, but also to target better the next generation of research.

For groundwater, a sizeable improvement in supply can be achieved by moving from poor to good catchment management under medium rainfall conditions, but not under poor or good rainfall. For improved surface water and improved soil moisture, it is particularly under low rainfall conditions that it is worth moving from poor to good catchment management. It is clear from the results that physical catchment management on its own is incapable of having a major impact on peoples' livelihoods other than within a very narrow range of parameters. The suggestion is that outside this range, the decision as to whether or not to take a physical catchment management approach has a negligible impact on water resources and even less on livelihoods. In relative terms a number of factors both extraneous (wider economy, underlying geology), and internal (community cohesion, skills levels) to the community rank equally or more highly in terms of general impact on well being.

Introduction

The Romwe catchment is a small headwater (4.5km^2) catchment of the Runde river, located about 80km south of Masvingo, provincial capital of Masvingo district. The catchment community of approximately 250 people are mainly engaged in dryland agriculture, although with a rapidly increasing number also undertaking small scale irrigation using groundwater (Moriarty and Lovell, 1997). The catchment has an extensive network of instruments modelling physical hydrology, and the community of the catchment and surrounding area have taken part in extensive participatory surveying to investigate the role of groundwater in their livelihoods (Moriarty and Lovell, 1999).

The objective of the paper is to bring together, within a single holistic framework, the principle findings of the research into the physical and human aspects of the study. The framework is used to integrate quantitative findings regarding a physical investigation of the catchment water resources and more qualitative information about their role within the livelihoods of the catchment community. It presents these findings in a reasonably objective and transparent manner, and allows them to be analysed to draw conclusions about the opportunities and constraints for further development of catchment water resources. In

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addition it is used to assess the merits and demerits of adopting a micro-catchment oriented management approach to natural resource management.

The framework is developed using Bayesian Belief Networks (BBNs) to identify and model the central aspects of both physical and human environment (at both the micro and macro scale), and their impacts on and, linkages too, each other. It identifies the conditions under which increased water resource use is most likely to occur, and the subset of these conditions within which micro-catchment management might be an appropriate management paradigm. By taking this approach the framework becomes the core of a decision support system that, by encapsulating the expert knowledge derived form this study, could be used to make management decisions other similar settings. In this paper the term catchment management is used to describe the physical and technical aspects of management, not the institutional ones.

Background to decision support systems

What is a Decision Support System?

At its most basic level, a decision support system (DSS) is a coherent framework that helps people to make decisions about a system in which they are interested. In this work the term is used to encompass computer based systems that provide a framework into which an actor may enter information and out of which will come advice or guidance on what decision to take to achieve some pre-defined goal. While 'expert systems' have been around since the early 1960s, there has been a shift in emphasis from systems that sought to model 'the best expertise in the world' and hence replace the 'expert' or 'manager' to systems that seek to model the domain or system, and to support the 'expert' or 'manager' in making decisions about it (Jensen, 1996).

For this study a decision support system is taken to be a framework of rules and relationships that represent a model of a 'problem domain, and which when presented with specific information about the problem domain will provide answers based on clear and transparent rules. The term 'problem domain' has been coined to describe the variables, linkages, and interactions within a system that have an *important* impact on a problem, question or hypothesis about some other part of the system. When dealing holistically with many aspects of a system the definition of boundaries is crucial and clearly defining the extent and boundaries of the problem domain is essential to satisfactory development of the DSS.

As important as defining the problem domain to be dealt with by the DSS, is clearly identifying the end user and ensuring that the output is tailored to their needs and is relevant to the task to which they wish to put it (Fritsh, 1999).

Important aspects of a decision support system

A DSS should provide a clear and coherent framework so that all stakeholders with interests in a given problem domain may clearly visualise and agree upon the important relations between different sections of the domain. In particular it should make explicit the more important underlying assumptions and tradeoffs implicit in making choices between different actions.

The following key points should be central to any DSS that seeks to serve as a basis for participatory and consensual decision making

- Ensures all necessary/available information collected – helps identify alternative sources
- Clearly identifies assumptions that are being made, and explicitly defines uncertainty
- Clearly identifies 'prejudices' of those making the decision
- Ensures that all things are 'properly' (consensualy) weighted for making a final decision
- Ensures that all important cause-effect relationships are identified, and their implications considered
- Allows for new decisions to be made in the light of new information and attitudes (Cain et al, 2000)
- Encourages appropriate stakeholder participation in decision making – rejects decisions where insufficient consensus exists

Bayesian Belief Networks – a new framework for decision support

The tool used to develop the DSS framework is a Bayesian Belief Network (BBN), a powerful system for the analysis of causal relationships under uncertainty. BBNs were chosen for this work because they explicitly acknowledge that they model beliefs – in this case *my* beliefs (knowledge) about the systems *I* have been researching for the last 3 years – rather than some external and 'objectively valid' reality. The networks therefore serve to bring together, in a transparent and testable manner, the findings of the work and the hypotheses developed from the findings.

A key strength of BBNs is their ability to integrate real (measured) and 'knowledge based' information and the associated uncertainty related to the information. In modelling complex systems with limited data availability the ability to expressly acknowledge uncertainty, and quantify its effects is crucial.

BBNs can learn. That is, in they can change the underlying relations between nodes on the basis of new data. To do this a BBN is linked to a knowledge base (data base) into which key data from monitoring and evaluation is entered. As more data is entered the probabilistic relationships between nodes will become increasingly sure (as long as the underlying logic of the connections is correct) (Cain et al, 2000). This is a particularly important feature where an adaptive management approach is to be taken to a problem and it is implicit within the management approach that change can and should be made in the light of experience.

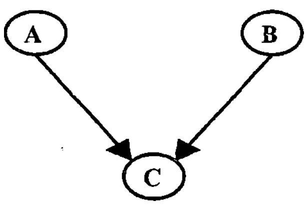
A final important advantage of using BBNs is the ability to use the structure of nodes and links to move away from classic modelling concepts such as 'variables', 'sources', and 'sinks'. A node may represent a variable in the classic modelling sense, however it may equally well represent a concept – nodes may thus be labelled in terms that come close to representing natural language (Cain et al, 2000); a node may represent 'community ability to work together', which can have 'good' or 'bad' states. It is important that concepts are clearly defined, and where possible open to some kind of more objective appraisal. For instance a node representing 'community ability to work together' may incorporate more concrete concepts such as 'number of successful community projects undertaken in the past'. Despite the need for clear definitions and the potential for confusion where these do not exist, the ability to represent nebulous but clearly important concepts is crucial to developing frameworks which allow the decision making process to be more transparent and with otherwise invisible mechanisms and assumptions laid bare to critical examination.

Bayesian Belief Networks

Bayesian Belief Networks are a powerful modelling tool that are based on the underlying premises of Bayes', rule a central axiom of probability theory.

BBNs allow a large number of causal relationships between variables (called 'nodes') to be linked together in a network, into which observations (referred to as 'findings') may be entered. The effects of these observations on other elements of the graph are then modelled. Each node has a number of distinct 'states', with a probability associated with each one. States may be words, phrases, or numerical ranges.

Each node in a BBN is underlain by a 'conditional probability table' which gives the probabilities associated with each of its possible states for all combinations of states of the nodes feeding into it ('parent' nodes). The diagram shows a causal diagram and conditional probability table for a node (C) with two parents (A, B).



A	B	C	
		true	false
true	false	0.8	0.2
false	true	0.2	0.8
true	true	0.5	0.5
false	false	0.5	0.5

In this example each of the nodes may have one of two states – true or false, and the table gives the probability for C to be in each of those states for all permutations and combinations of the states of its parent nodes. The sum of probabilities for each combination of states will always be one. The conditional probability table therefore states that, 'if A is true, and B false, there is an 80% probability that C is true'.

In its baseline state, a BBN reflects the spread of probabilities for all nodes, as soon as findings start to be entered into it the uncertainty associated with the entire network will start to diminish, and the range of possible states becomes constrained.
(Jensen, 1997)

BBNs may be used at a number of different levels of complexity. At the simplest they can act as a check list of the factors and linkages seen as important in a system – this conforms to the initial stage of model development, when the network is first designed and nodes are linked to each other in a directed acyclic graph (*acyclic* refers to the fact that feedback loops may not be modelled within a single time-step; while BBNs can be used to model multiple time steps the complexity quickly becomes unmanageable, and this approach has not been used). At the next level they may be used to model opinion as to how the system works, using qualitative definitions such as 'good' or 'bad'; 'true' or 'false'. Finally, they may be used to incorporate 'hard' data in relationships that are based on either observed data (stochastic) or process based modelling (deterministic). The BBNs in this paper have been developed at the first and second levels; that is insights from the Romwe case study are used to develop a framework, which is then validated using 'expert knowledge', derived from the case study.

Since the early 1990s Bayesian Belief Networks have been viewed with increasing interest by ecologists and natural resource managers as offering a new and promising approach to decision support (Cain et al, 1999a and 1999b; Anderson, 1999; Jensen, 1996; Varis, 1998).

Towards developing a decision support framework

Defining a problem domain

Key to designing a DSS is defining the problem domain for which decision support is desired: a poorly bounded framework will quickly become unwieldy and incapable of producing useful outputs.

Given this study's principal focus on water resources and their role within rural livelihoods, and the added interest in micro-catchment management as a possible approach to improving the of water resources base it is clear that the decision support system should be based around these two issues.

The central 'problem' to be investigated using the framework is therefore defined as being the '*identification of the likelihood that catchment management will have a positive impact on livelihoods through improved access to, and management of, water resources*'. The problem domain is therefore all aspects of the catchment 'system' that are relevant to this problem.

For the purpose of this study the 'user' is me, the author. However, in the longer term the framework could become the core of a DSS or 'expert system', encapsulating my expert knowledge for use by someone else.

Micro-catchment management within the context of the problem domain refers only to some collection of physical interventions aimed at having a positive impact on a specified aspect of the water resource. The definition of micro-catchment is also assumed to refer to the 'hard' catchment – that is the geographical unit contributing to the water resource of interest. This is a very narrow definition, and its limitations are discussed in the conclusions. Water resource use is to be understood in the widest possible sense and includes both distributed (soil moisture) and point (ground and surface water) sources. While this study has concentrated largely on groundwater, it is important to keep in mind that, despite all the evidence of rapid rise in the use of point water sources, the community continues to focus primarily on rainfed agriculture.

While micro-catchment management may have positive impacts on other resources, both common pool and private, this is not explicitly included in the DSS. The DSS is solely interested in the effects of catchment management on water resources, and through these on livelihoods.

Methodology of DSS development

The development of the conceptual framework for the DSS was undertaken using a number of iterative steps, underlain by the general principle that the system should be developed only to the level of complexity necessary to give useful output within the given problem domain whilst minimising the necessary data input. Having determined the problem space for the decision support system, the next step was to outline at the simplest level the main 'aspects' of the system to be modelled and from there to progressively add levels of complexity until a satisfactory balance between useful output and minimising data requirements could be achieved.

At each level of development the system was tested for responsiveness to input. The utility of the framework was then tested by running a number of scenarios through it to assess its ability to analyse the problem domain and to identify key data needs to make the necessary decisions. Finally the completed framework was used to examine the concept of catchment management as an alternative to other forms of management – and to try to highlight those areas where a switch might be justified.Development and testing of frameworks

First step towards a holistic framework - a high level conceptual model

Figure 1 shows the first high level belief network (along with its conditional probability tables - CPTs) developed to model the problem domain. This network represents the core groups of factors affecting water resources and their role in livelihoods, as well as the possible effects of catchment management interventions upon them. At this level concepts remain vague, and the network is included as an extended example of how BBNs work. The network diagram appears exactly as it does in the Netica software, with the numbers and graphs representing the levels of belief attached to each state within a node.

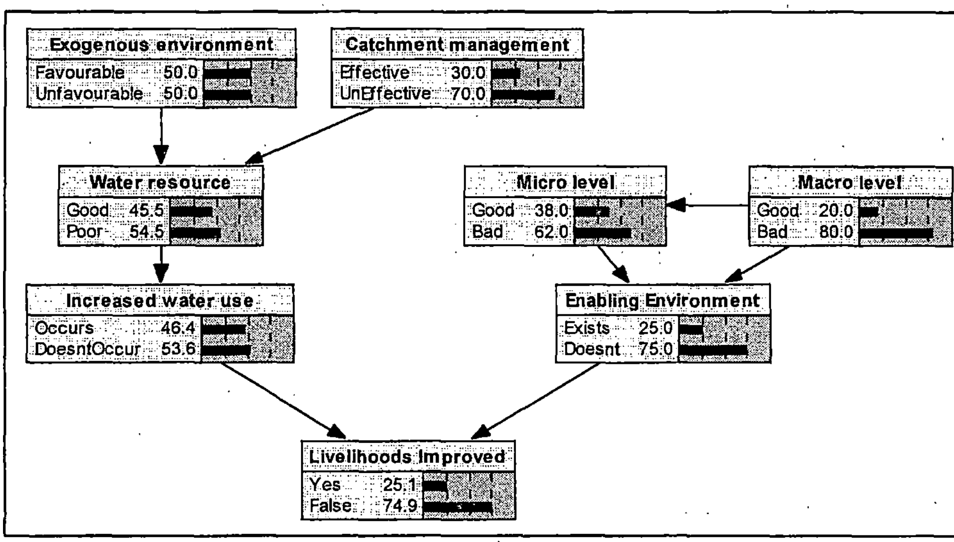
The network is constructed so that it is the effect on livelihoods that is at the heart of the system. The *enabling environment* node encompasses most of the 'human' side of the work (with *micro level* and *macro level* representing the local level and wider world respectively); whilst *exogenous environment* represents the 'physical' side.

For decision making purposes findings are first be entered for *exogenous environment*, *micro level*, and *macro level*, following which it becomes possible, by entering a finding in *catchment management*, to assess the likely impact of effective catchment management on the probability of livelihoods improving. Figure 2 and Figure 3 show the effects on *livelihoods* of entering findings into the simple network. The relative lack of effect on the network of varying the effectiveness of catchment management (the probability of livelihoods improving changes by approximately than ten percent) reflects the overriding importance of external factors, both physical and human.

Even with all findings 100% favourable, *livelihoods improved* only achieves a 72.8% chance of being 'true', or, put another way, there is still a 27.2% probability that livelihoods won't improve. This reflects underlying uncertainty within my *beliefs* in the system, both on how *exogenous environment* and *catchment management* influence increased water use, and how *increased water use* and *enabling environment* affect livelihoods.

A useful feature of the Netica software is that it allows easy sensitivity analysis to be carried out on the impact on the level of uncertainty associated with a selected 'target' node of information entered into other 'findings' nodes. A weakness of the software is that it only evaluates the effect of a single finding at a time, assuming the rest of the network to remain constant. This in turn allows an indirect measure of the relative importance of the findings nodes in terms of the target node. Hence it gives no measure of the effects of different combinations of findings (Norsys, 1997). To investigate this it is necessary to manually enter findings in some nodes and then carry out the sensitivity analysis again.

The measure used to judge the effect is called *entropy reduction.* Entropy is a measure of how the probability distribution is spread between the states at a given node (Jensen, 1996; p125). Maximum entropy exists when the probability distribution is equal across all states – so for a node with two states, a distribution of 0.5, 0.5; minimum exists when all the probability is at one state -- so 1, 0 or 0, 1. Entropy reduction is the difference in entropy at the target node before and after a finding is entered in one or more findings node. The maximum value for entropy reduction is therefore 1, an unlikely finding given that it indicates that findings at a single node in the network explain 100%, whilst the minimum is 0, indicating that the findings node is disconnected from the target node. The values for entropy reduction are calculated using a log2 relationship, so are not directly comparable, i.e., a finding that causes an entropy reduction of 0.1 will not have ten times the effect of one that causes a reduction of 0.01. Entropy reduction is therefore used simply to rank findings in order of important. Entropy reduction is therefore a quick and easy method to rank the importance of findings, which can then be more fully investigated using direct comparison of the effects of findings.



Increased Water Use	Enabling environment	Livelihoods improve	
		Yes	No
Occurs	Exists	0.8	0.2
Occurs	Doesn't	0.3	0.7
Doesn't occur	Exists	0.4	0.6
Doesn't occur	Doesn't	0	1

Water Resource	Increased Water Use	
	Occurs	Doesn't occur
Good	0.9	0.1
Poor	0.1	0.9

Micro level	Macro level	Enabling Environment	
		Exists	Doesn't
Good	Good	0.8	0.2
Good	Bad	0.5	0.5
Bad	Good	0.3	0.7
Bad	Bad	0	1

Catchment Management	Exogenous factors	Water Resource	
		Good	Poor
Effective	Favourable	0.9	0.1
Effective	Unfavourable	0.5	0.5
Ineffective	Favourable	0.6	0.4
Ineffective	Unfavourable	0.1	0.9

Macro level	Micro level	
	Good	Bad
Good	0.7	0.3
Bad	0.3	0.7

Macro level	
Good	Bad
0.2	0.8

Exogenous factors	
Favourable	Unfavourable
0.5	0.5

Catchment Management	
Effective	Ineffective
0.3	0.7

Figure 1 Highest level Belief Network of problem domain

For decision making purposes findings are first be entered for *exogenous environment, micro level,* and *macro level,* following which it becomes possible, by entering a finding in *catchment management,* to assess the likely impact of effective catchment management on the probability of livelihoods improving. Figure 2 and Figure 3 show the effects on *livelihoods* of entering findings into the simple network. The relative lack of effect on the network of varying the effectiveness of catchment management (the probability of livelihoods improving changes by approximately than ten percent) reflects the overriding importance of external factors, both physical and human.

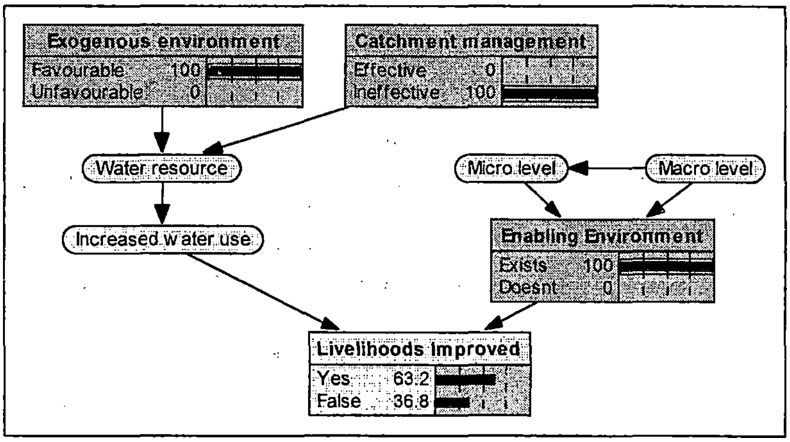


Figure 2 Effect on livelihoods of ineffective catchment management

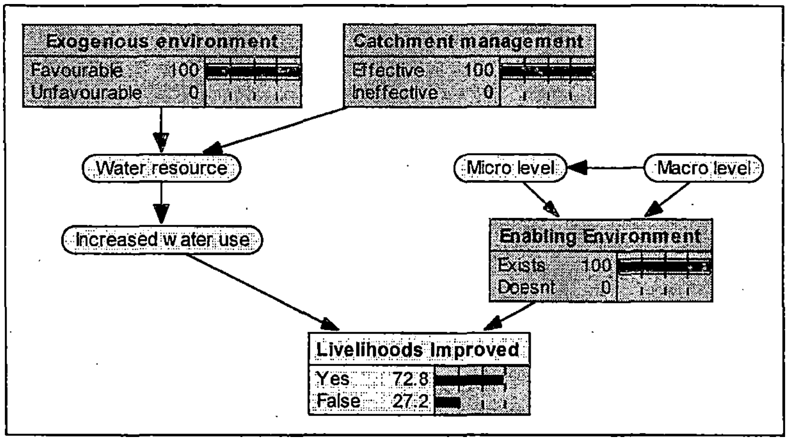


Figure 3 Effect on livelihoods of effective catchment management

Even with all findings 100% favourable, *livelihoods improved* only achieves a 72.8% chance of being 'true', or, put another way, there is still a 27.2% probability that livelihoods won't improve. This reflects underlying uncertainty within my *beliefs* in the system, both on how *exogenous environment* and *catchment management* influence increased water use, and how *increased water use* and *enabling environment* affect livelihoods.

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The measure used to judge the effect is called *entropy reduction.* Entropy is a measure of how the probability distribution is spread between the states at a given node (Jensen, 1996; p125). Maximum entropy exists when the probability distribution is equal across all states – so for a node with two states, a distribution of 0.5, 0.5; minimum exists when all the probability is at one state – so 1, 0 or 0, 1. Entropy reduction is the difference in entropy at the target node before and after a finding is entered in one or more findings node. The maximum value for entropy reduction is therefore 1, an unlikely finding given that it indicates that findings at a single node in the network explain 100%, whilst the minimum is 0, indicating that the findings node is disconnected from the target node. The values for entropy reduction are calculated using a log2 relationship, so are not directly comparable, i.e., a finding that causes an entropy reduction of 0.1 will not have ten times the effect of one that causes a reduction of 0.01. Entropy reduction is therefore used simply to rank findings in order of important. Entropy reduction is therefore a quick and easy method to rank the importance of findings, which can then be more fully investigated using direct comparison of the effects of findings.

Table 1 Effects on Livelihoods Improved node of entering findings in other nodes

		Entropy reduction	
Enabling Environment	0.131	0.142	Exists
Exogenous Factors	0.014	Unfavourable	Unfavourable
Catchment Management	0.007	0.010	0.010

Table 1 shows the effects on entropy in the *livelihoods improved* node of entering findings about *enabling environment, exogenous factors, and catchment management.* The table shows the effects on entropy reduction with no initial findings entered in the network (column 1); with an 'unfavourable' finding entered in *exogenous factors* environment (column 2); and with both an 'unfavourable' finding for *exogenous factors* and an 'exists' finding for *enabling environment.* With no findings entered, *enabling environment* comes out as being most important. It has approximately nine times higher entropy than *exogenous factor*s, which in turn has two times higher values than *catchment management.* However, it can be seen that, once findings are entered for *exogenous environment* and *enabling environment,* the effects of a finding as to whether catchment management is carried out or not becomes more relevant. An important point that relates to how values for entropy reduction are calculated, is that the fewer intermediary nodes between a findings node and the target node of interest, the greater the effect on entropy, all other things being equal. This is because uncertainty in intermediate nodes has the effect of damping the effects of findings as they are transmitted along the causal chain.

This network is too coarse to identify more clearly the particular ranges for other parameters for which catchment management may have a beneficial effect on water resources, and so it is necessary to develop a more complex model to further investigate this and other issues. In general however, whether catchment management is carried out or not has only a marginal effect on livelihood improvement when compared to exogenous factors such as the external economy, or a generally good enabling environment. Already this network outlines the thinking behind an important policy implication of the Romwe work; namely that micro-catchment management is an approach that should be adopted, if at all, on a case by case basis rather than as an across the board management intervention.

The main problem domain BBN

A number of intermediate models that are not shown here were developed between the high level model (Figure 1) and the final decision support framework (Figure 4). Each model brought more complexity to the overall picture, but was found to be lacking some important element. The model in Figure 4, while still having some fairly broadly based variables, is of the correct level of detail to identify the major factors and trade-offs involved in identifying the most effective set of conditions for intervention within the problem domain. The network remains defined in largely qualitative terms, as a single case study gives insufficient evidence on which to base quantitative output, the data in the CPTs therefore represents my opinion (expert knowledge) based on the findings from this study. Nodes and links are added either because they were highlighted by findings from the project, or because they are widely acknowledged within the literature or expert opinion to be important

The model is derived for use at the micro-catchment scale, the time-step is undefined, but should be considered as being 'short term'. The framework is presented in a diagram, followed by a narrative description which talks through the major relationships described in the model.

As it stands the model represents a conceptual framework with qualitative descriptors. Its use would be as a tool for preliminary analysis of a potential project site. Study data could be used to give some quantitative support to some of the relationships, however given the size of the sample this would be of very limited value. A framework such as this would need to be based on a knowledge base of hundreds if not thousands of examples before it would be possible to truly validate the rules.

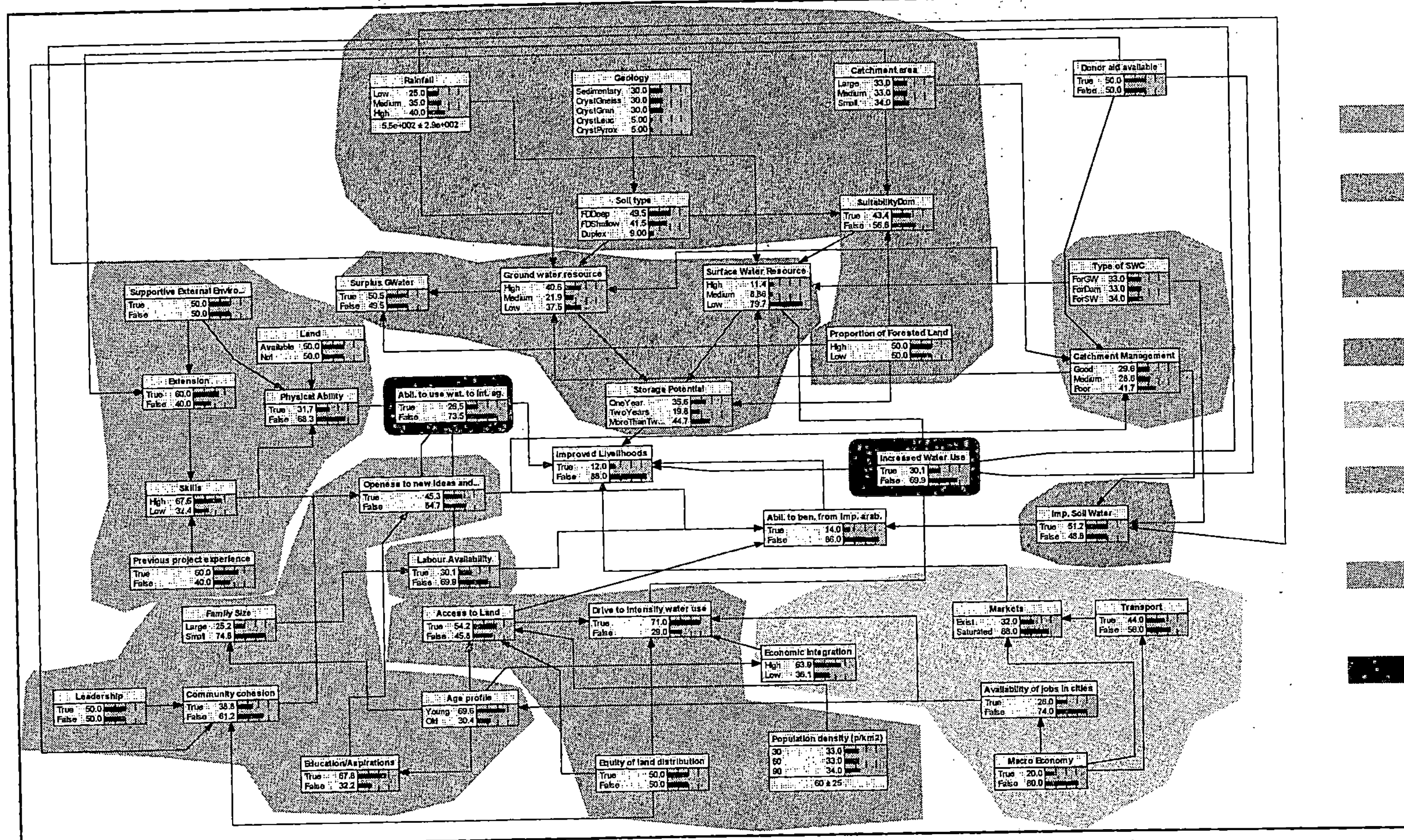

Figure 4 Bayesian Belief Network of likelihood of a catchment management intervention having a favourable impact on livelihoods

Catchment management network narrative

The Network is subdivided into a number of major groups of nodes dealing with different aspects of the system. These groupings are:

physical base
water resources
community physical ability
community social/institutional ability
drivers to increased water use
external economy
ability to use water

The groupings correspond to nodes on one of the intermediate BBNs mentioned above. The narrative attached to the BBN explains in general terms how these groupings relate to each other, and highlights the most important relationships within them.

Physical Base (see Figure 5 for CPTs)
This group deals with the major aspects of the physical environment and how they affect the available water resources within the study area. Nodes include *rainfall, geology, soil type, catchment area, suitability for dam,* and *proportion of forested land.*

Rainfall is seen as a key external driver to the entire system, impacting directly on ground and surface water resources. *Geology* affects water resources through its relationship with *soil type*, for which it is the sole causal agent; simple relationships based on observed data in the Romwe catchment and elsewhere indicate for example, that pyroxene gneisses (*CrystPyrox*) will give rise to deep freely draining soils (*FDDeep*), while Leucocratic gneisses will give rise to either freely draining shallow (*FDShallow*) or duplex soils. At a coarser level of distinction geology can be subdivided into sedimentary, gneiss (*CrystGneiss*) or granitic types (*CrystGran*), which give mixes of soil characteristics. The relative proportions assigned to soil types based on Geology are derived from the Romwe catchment. *Suitability for dam* represents the likelihood that an area will be physically suitable for dam construction, it is affected by *catchment area, soil type,* and *proportion of forested land.* In general medium sized catchments are seen as being most suitable for small dams (too small and the water resource is insufficient, too large and the dam will be too small and hence silt quickly), however there is a high degree of uncertainty in all the relationships (see conditional probability table), as many other factors affecting dam suitability are left out (e.g. topography). Again, a finding in the *suitability for dam* node will lead to redundancy of information about its parents. Finally proportion of forest land is included primarily to reflect the importance of the findings from the study on groundwater use by deep rooted vegetation (Lovell et al, 1998) although forest is also seen as having a moderating and reducing effect on rainfall for surface water storage (through runoff attenuation and increased soil moisture use).

Catchment management (see Figure 6 for CPTs)
This group consists of only two nodes, *catchment management* and *type of SWC* and represent the type of approach taken to catchment management and the quality of its implementation. *Type of SWC* represents an important concept within the DSS. This is that soil and water conservation measures undertaken as part of a catchment management programme will broadly speaking fall into one of three groupings. These are

1. those interventions aimed primarily at improving groundwater recharge (*ForGW*), for example large contour bunds that allow concentration of infield runoff
2. those aimed primarily at arable production, and hence soil moisture conservation (*ForSM*)
3. those aimed at surface water (*ForDam*) which will primarily be focussed on reducing siltation.

An important point regarding how the network is constructed is *my* belief that for at least some conditions of rainfall there are important tradeoffs between each of these approaches, and that these must be explicitly acknowledged.

Water resources (see Figure 12 and 13 for CPTs)

This group lies at the heart of modelling beliefs as to how the physical environment and the type of catchment management carried out interact to effect the availability of water resources. It includes nodes for *surplus groundwater, groundwater resource, surface water resource*, and *storage potential. groundwater resource* is controlled entirely by *soil type, rainfall, catchment management* and *type of SWC* with the first two dominating in most cases. *Catchment management* is seen as having a potentially important positive effect if done to maximise groundwater recharge (e.g. larger infield structures that trap runoff and allow it to infiltrate), or negative if done to maximise soil and water conservation – however these effects only become dominant when rainfall is medium. This reflects the effects of non-linearity in rainfall-recharge-runoff relationships, and specifically Butterworth's (1997) finding that in a year with evenly distributed rainfall of ~700mm recharge only happened in areas where runoff was concentrated. Equally it incorporates findings by Moyo & Hagman (1994) and Moyo (1998) showing that it is possible to reduce runoff to close to zero by using in-field water conservation measures such as tied ridges, and thus presumably reducing or eliminating groundwater recharge.

This is one of the key points which the network seeks to highlight. Catchment management can be an important agent in water resources management, but its effects will only be important in marginal conditions, and then there will be tradeoffs between different management approaches on different compartments of the water resource.

Surface water resources are effected by *catchment management* and *rainfall*, also by *suitability for dam* which effectively acts as an on/off switch, i.e. if a dam site does not exist surface water resources are automatically set to low. *Surplus groundwater* is affected by a combination of groundwater availability and proportion of forest. It feeds into the *increased water use* node which is an important interface between the physical and social aspects of the catchment. High water resources act as a switch as to whether a demand and ability to use water resources can be turned into an improvement in livelihoods. *Groundwater* and *surface water resources* affect *improved livelihoods* through *increased water use* and *storage potential*. *Storage potential* represents the sustainability of the water resource, and is conditioned to prefer groundwater to surface water sources reflecting the former's greater ability to buffer against low rainfall as evidenced by the widespread failure of many small dams during times of drought. Once again it is underlined that where more detailed information about the storage potential of a given water source is known it may be entered directly into the node. Finally *improved soil water* allows for arable production to be taken into account by modelling the effects of improved soil and water conservation.

Community physical ability (see Figure 7 for CPTs)
Community physical ability refers specifically to the ability to carry out community projects. It is seen as being driven by a mixture of skills, assets, and a suitable external environment. The group includes nodes for *supportive external environment, extension, skills, previous project experience, labour availability,* and *land.* Land in this case refers to the existence of land on which a project may be undertaken and reflects the utilitarian reality that if land can't be found the project is unlikely to be successful, if it is absent *physical ability* is set to low.

Supportive external environment covers a number of important drivers that are lumped together as being largely beyond the scope of a micro-catchment project to affect. It includes areas such as laws and by-laws, rural district council support and co-operation, and availability of help, advice, and credit. *Extension* is frequently identified at workshops and in the literature as being of particular importance to facilitate the processes surrounding development of successful projects, and is in turn seen as being considerably helped by the presence of a *donor*. Skills are developed by good extension, but an existing skills base may be indicated by previous examples of community experience of carrying out projects (*previous project experience*).

Previous project experience rests upon another important hypothesis of this work – that the reason small scale irrigation has proved so popular and successful in the Romwe area is that it is already an activity to which the community is committed, although still lacking in certain key skills (e.g. pest and disease control), and in which it has begun to develop key skills. The node seeks to differentiate between communities with some previous experience, and those with none whatsoever.

Finally *labour availability* is seen as being a crucial variable, affecting the likelihood of a community to tend towards more or less intensive forms of agriculture. For example a high labour availability in conjunction with good access to land will bias a community towards livelihoods based around rainfed crop production, on the other hand low *labour availability* and low *access to land* will tend towards communal and intensified forms of production.

Community social/institutional ability (see Figure 8 for CPTs)
This large group of nodes is closely linked to the Community physical ability section and together they drive the *ability to use water to intensify agriculture* node, which itself has a direct impact on improved livelihoods. The group contains nodes for *leadership, community cohesion, education/aspirations, age profile, and openness to new ideas and experiences.*

The importance of *leadership* is a consistent theme that runs through the participatory and development literature. Wherever community projects are to be undertaken it is clear that failure to identify and promote good leadership will lead to wider project failure. Of equal importance is *community cohesion* - a term coined to reflect a community's ability to work together towards common goals – the opposite of a cohesive community being a fragmented community which is one where the pull of individual desires and aspirations militates against the ability to work together. In this case *community cohesion* is seen as being driven by a combination of leadership and equity in land distribution – it is also seen as something that it is possible to enhance by the availability of *donor aid.* It is in turn seen as being an important cause of *openness to new ideas and experiences,* a key node in deciding whether there is an ability to benefit from improved water management. While the effect of family size on labour availability is conjectural (although also seemingly logical), the move by young people to having smaller families was strongly supported by the output of participatory sessions in Village D and is behind the link between *age profile* and *labour availability*. The *age profile* of a community is one of the key variables to have come from surveying work carried out with the community. It affects a wide range of variable within the 'Social and institutional ability' section, including *access to land, openness to new ideas, education/aspirations and economic integration* all of which were listed as important drivers to change by young people in Village D. All the variables apart from *access to land* improve with a younger age profile. Access to land decreases for young people.

Ability to use water (see Figure 9 for CPTs)
Crucial to the likelihood of catchment management and improved water resource management having a beneficial effect on livelihoods is the ability of the target group (community or individuals) to benefit from the extra water made available. This concept is explicitly recognised by the inclusion of two nodes to represent the use of point (ground or surface) or distributed (soil moisture) water, respectively *ability to use water to intensify agriculture* and *ability to benefit from improved arable*. Both of these nodes bring together a number of key variables from the 'community physical ability' and 'community social/institutional ability' groups.

Drivers to increased use (see Figure 11 for CPTs)
This group deals with factors that while largely external to, or at least unlikely to be affected by changes in catchment management or water resource development, are important drivers towards increased water resource use. It contains nodes for *equity of land distribution, population density, drive to intensify water use,* and *access to land.* While other sections condition the likelihood of catchment management and water resources development to have a positive impact on livelihoods, the 'drivers to increased use' are, as the name implies, largely causal agents for such change. They are all linked in some way to the famous population/land nexus, and can be simply summed up by saying that decreasing access to land will lead to increasing efforts to intensify farming systems and hence a tendency towards the development of point as opposed to distributed water resource systems.

External economy (see Figure 10 for CPTs)
As with drivers to increased use, the external economy group is considered as being largely external to the 'catchment'. The group contains nodes for *macro-economy, markets, transport, and availability of jobs in cities*. While it is clearly possible for a community to expand existing markets or develop new ones, the overall existence of markets for agricultural produce will largely depend on the wider health of the macro-economy. However, available markets for produce, be it from rainfed fields, irrigated crops or other sources of production, will inevitably have a crucial impact on any scheme to improve livelihoods, and as such they are one of the four parents of the improved livelihoods node.

			Suitability for dam	
Area	Soil type	Forest	True	False
Large	FDDeep	High	0.2	0.8
Large	FDDeep	Low	0.2	0.8
Large	FDShallow	High	0.1	0.9
Large	FDShallow	Low	0.1	0.9
Large	Duplex	High	0.1	0.9
Large	Duplex	Low	0.1	0.9
Medium	FDDeep	High	0.7	0.3
Medium	FDDeep	Low	0.7	0.3
Medium	FDShallow	High	0.7	0.3
Medium	FDShallow	Low	0.7	0.3
Medium	Duplex	High	0.7	0.3
Medium	Duplex	Low	0.7	0.3
Small	FDDeep	High	0.4	0.6
Small	FDDeep	Low	0.4	0.6
Small	FDShallow	High	0.5	0.5
Small	FDShallow	Low	0.5	0.5
Small	Duplex	High	0.5	0.5
Small	Duplex	Low	0.5	0.5

Global climate change	
Drier	Wetter
0.5	0.5

Catchment area		
Large	Medium	Small
0.33	0.33	0.34

Proportion forested land	
High	Low
0.5	0.5

	Position in rainfall cycle	
Global climate	Wet	Dry
Drier	0.4	0.6
Wetter	0.6	0.4

	Soil type		
Geology	FDDeep	FDShallow	Duplex
Sedimentary	0.8	0.2	0
Cryst. Gneiss	0.5	0.3	0.2
Cryst. Gran	0.2	0.8	0
Cryst. Leuc	0	0.4	0.6
Cryst. Pyrox	0.9	0.1	0

		Rainfall		
Rainfall cycle	Global climate	Low	Medium	High
Wet	Drier	0.25	0.35	0.4
Wet	Wetter	0.2	0.3	0.5
Dry	Drier	0.4	0.5	0.1
Dry	Wetter	0.5	0.4	0.1

Geology				
Sedimentary	Cryst. Gneiss	Cryst. Granite	Cryst. Leuc.	Cryst. Pyrox.
0.3	0.3	0.3	0.05	0.05

Figure 5 Conditional probability table for 'physical base' group

			Catchment management		
Donor	Openness	Area	Good	Medium	Poor
True	True	Large	0.5	0.3	0.2
True	True	Medium	0.65	0.2	0.15
True	True	Small	0.8	0.15	0.05
True	False	Large	0.05	0.2	0.75
True	False	Medium	0.1	0.3	0.6
True	False	Small	0.2	0.3	0.5
False	True	Large	0.4	0.3	0.3
False	True	Medium	0.5	0.3	0.2
False	True	Small	0.6	0.3	0.1
False	False	Large	0	0.2	0.8
False	False	Medium	0	0.4	0.6
False	False	Small	0	0.5	0.5

Type of SWC		
For GW	For dam	For SW
0.33	0.33	0.34

Figure 6 Conditional probability table for 'catchment management'

Extension	Previous experience	Skills	
		High	Low
True	True	0.9	0.1
True	False	0.6	0.4
False	True	0.8	0.2
False	False	0.1	0.9

Family size	Labour availability	
	True	False
Large	0.6	0.4
Small	0.2	0.8

Previous project experience	
True	False
0.6	0.4

Land	
Available	Not
0.5	0.5

Supportive external environment	
True	False
0.5	0.5

Supportive external environment	Donor	Extension	
		True	False
True	True	1	0
True	False	0.6	0.4
False	True	0.7	0.3
False	False	0.1	0.9

Figure 7 Conditional probability table for 'community physical ability'

Labour availability	Openness	Soil water	Land pressure	Ability to benefit from improved arable	
				True	False
True	True	True	True	0.9	0.1
True	True	True	False	0.3	0.7
True	True	False	True	0.1	0.9
True	True	False	False	0.1	0.9
True	False	True	True	0.5	0.5
True	False	True	False	0	1
True	False	False	True	0.1	0.9
True	False	False	False	0	1
False	True	True	True	0.2	0.8
False	True	True	False	0.1	0.9
False	True	False	True	0	1
False	True	False	False	0.1	0.9
False	False	True	True	0.2	0.8
False	False	True	False	0	1
False	False	False	True	0.1	0.9
False	False	False	False	0	1

Openness	Labour availability	Physical ability	Ability to intensify agriculture	
			True	False
True	True	True	0.9	0.1
True	True	False	0.4	0.6
True	False	True	0.8	0.2
True	False	False	0.2	0.8
False	True	True	0.5	0.5
False	True	False	0.2	0.8
False	False	True	0.1	0.9
False	False	False	0	1

Figure 8 Conditional probability table for 'community social/institutional ability'

Job availability	Land equity	Land pressure	Economic integration	Drive to intensification	
				True	False
True	True	True	High	0.7	0.3
True	True	True	Low	0.5	0.5
True	True	False	High	0.3	0.7
True	True	False	Low	0.1	0.9
True	False	True	High	0.7	0.3
True	False	True	Low	0.5	0.5
True	False	False	High	0.8	0.2
True	False	False	Low	0.6	0.4
False	True	True	High	0.7	0.3
False	True	True	Low	0.5	0.5
False	True	False	High	0.8	0.2
False	True	False	Low	0.7	0.3
False	False	True	High	1	0
False	False	True	Low	0.9	0.1
False	False	False	High	0.7	0.3
False	False	False	Low	0.5	0.5

Age	Land equity	Population	Land pressure	
			True	False
Young	True	30	0.2	0.8
Young	True	60	0.5	0.5
Young	True	90	0.8	0.2
Young	False	30	0.4	0.6
Young	False	60	0.7	0.3
Young	False	90	1	0
Old	True	30	0	1
Old	True	60	0.4	0.6
Old	True	90	0.7	0.3
Old	False	30	0.1	0.9
Old	False	60	0.5	0.5
Old	False	90	0.7	0.3

Population density (people/k^2)		
90	30	60
0.34	0.33	0.33

Equity of land distribution	
True	False
0.5	0.5

Figure 9 Conditional probability table for 'Ability to use water'

Transport	Macro economy	Markets	
		Exist	Saturated
True	True	0.8	0.2
True	False	0.3	0.7
False	True	0.4	0.6
False	False	0.2	0.8

Macro economy	Job availability in cities	
	True	False
True	0.9	0.1
False	0.1	0.9

Macro economy	Transport	
	True	False
Good	0.6	0.4
Poor	0.4	0.6

Macro economy	
True	False
0.2	0.8

Figure 10 Conditional probability table for 'External economy'

Labour availability	Openness	Soil water	Land pressure	Ability to benefit from improved arable	
				True	False
True	True	True	True	0.9	0.1
True	True	True	False	0.3	0.7
True	True	False	True	0.1	0.9
True	True	False	False	0.1	0.9
True	False	True	True	0.5	0.5
True	False	True	False	0	1
True	False	False	True	0.1	0.9
True	False	False	False	0	1
False	True	True	True	0.2	0.8
False	True	True	False	0.1	0.9
False	True	False	True	0	1
False	True	False	False	0.1	0.9
False	False	True	True	0.2	0.8
False	False	True	False	0	1
False	False	False	True	0.1	0.9
False	False	False	False	0	1

Openness	Labour availability	Physical ability	Ability to intensify agriculture	
			True	False
True	True	True	0.9	0.1
True	True	False	0.4	0.6
True	False	True	0.8	0.2
True	False	False	0.2	0.8
False	True	True	0.5	0.5
False	True	False	0.2	0.8
False	False	True	0.1	0.9
False	False	False	0	1

Figure 11 Conditional probability table for 'drivers to increased use' group

Rainfall	SW conservation type	Soil type	Catchment management	Ground water resource		
				High	Medium	Low
High	ForGW	FDDeep	Good	1	0	0
High	ForGW	FDDeep	Medium	0.9	0.1	0
High	ForDam	FDDeep	Good	0.8	0.2	0
Medium	ForGW	FDDeep	Good	0.7	0.25	0.05
Medium	ForGW	FDShallow	Good	0.7	0.25	0.05
Medium	ForGW	Duplex	Good	0.7	0.25	0.05
High	ForGW	FDDeep	Poor	0.8	0.15	0.05
High	ForGW	FDShallow	Good	0.7	0.25	0.05
High	ForGW	FDShallow	Medium	0.6	0.35	0.05
High	ForDam	FDDeep	Medium	0.7	0.25	0.05
High	ForSW	FDDeep	Good	0.8	0.15	0.05
Medium	ForGW	FDDeep	Medium	0.6	0.3	0.1
Medium	ForGW	FDShallow	Medium	0.6	0.3	0.1
Medium	ForGW	Duplex	Medium	0.6	0.3	0.1
High	ForGW	Duplex	Good	0.7	0.2	0.1
High	ForDam	FDDeep	Poor	0.6	0.3	0.1
High	ForSW	FDDeep	Medium	0.7	0.2	0.1
High	ForSW	FDDeep	Poor	0.6	0.3	0.1
High	ForSW	FDShallow	Poor	0.6	0.3	0.1
High	ForSW	Duplex	Poor	0.7	0.2	0.1
Medium	ForDam	FDDeep	Good	0.6	0.25	0.15
Medium	ForDam	FDShallow	Good	0.6	0.25	0.15
High	ForGW	Duplex	Medium	0.6	0.25	0.15
High	ForGW	Duplex	Poor	0.5	0.35	0.15
Medium	ForGW	FDDeep	Poor	0.5	0.3	0.2
Medium	ForGW	FDShallow	Poor	0.5	0.3	0.2
Medium	ForGW	Duplex	Poor	0.5	0.3	0.2
Medium	ForDam	FDDeep	Medium	0.5	0.3	0.2
Medium	ForDam	FDDeep	Poor	0.4	0.4	0.2
Medium	ForDam	FDShallow	Medium	0.5	0.3	0.2
Medium	ForDam	FDShallow	Poor	0.4	0.4	0.2
Medium	ForDam	Duplex	Good	0.5	0.3	0.2
Medium	ForDam	Duplex	Medium	0.4	0.4	0.2
Medium	ForSW	FDShallow	Poor	0.4	0.4	0.2
High	ForGW	FDShallow	Poor	0.5	0.3	0.2
High	ForDam	FDShallow	Good	0.5	0.3	0.2
High	ForDam	FDShallow	Medium	0.4	0.4	0.2
High	ForDam	Duplex	Good	0.5	0.3	0.2
High	ForDam	Duplex	Medium	0.4	0.4	0.2
High	ForSW	FDShallow	Good	0.5	0.3	0.2
High	ForSW	FDShallow	Medium	0.4	0.4	0.2
High	ForSW	Duplex	Good	0.5	0.3	0.2
High	ForSW	Duplex	Medium	0.4	0.4	0.2
Medium	ForDam	Duplex	Poor	0.3	0.4	0.3
Medium	ForSW	Duplex	Poor	0.4	0.3	0.3
High	ForDam	FDShallow	Poor	0.3	0.4	0.3
High	ForDam	Duplex	Poor	0.3	0.4	0.3
Medium	ForSW	FDShallow	Medium	0.3	0.35	0.35
Medium	ForSW	FDDeep	Poor	0.3	0.3	0.4
Medium	ForSW	Duplex	Medium	0.3	0.3	0.4
Medium	ForSW	FDDeep	Medium	0.2	0.3	0.5
Low	ForGW	FDShallow	Good	0.1	0.3	0.6
Low	ForGW	Duplex	Good	0.1	0.3	0.6
Low	ForGW	FDDeep	Good	0.05	0.25	0.7
Medium	ForSW	FDDeep	Good	0.1	0.2	0.7
Medium	ForSW	FDShallow	Good	0.2	0.1	0.7
Medium	ForSW	Duplex	Good	0.2	0.1	0.7
Low	ForGW	FDShallow	Medium	0	0.2	0.8
Low	ForGW	Duplex	Medium	0	0.2	0.8
Low	ForGW	FDDeep	Medium	0	0.1	0.9
All remaining combinations give probability:				0	0	1

Figure 12 Conditional probability table for 'water resources' (continued overleaf)

Rainfall	Type of SWC	Suitability dam	Catchment man	Surface water resource		
				High	Medium	Low
High	ForDam	True	Good	0.7	0.25	0.05
High	ForGW	True	Good	0.6	0.3	0.1
High	ForGW	True	Medium	0.6	0.3	0.1
High	ForDam	True	Medium	0.6	0.3	0.1
High	ForSW	True	Good	0.6	0.3	0.1
High	ForSW	True	Medium	0.6	0.3	0.1
High	ForGW	True	Poor	0.5	0.35	0.15
High	ForDam	True	Poor	0.5	0.35	0.15
High	ForSW	True	Poor	0.5	0.35	0.15
Medium	ForDam	True	Good	0.4	0.4	0.2
Medium	ForDam	True	Medium	0.3	0.5	0.2
Medium	ForDam	True	Poor	0.2	0.4	0.4
Low	ForDam	True	Good	0	0.4	0.6
Low	ForDam	True	Medium	0	0.2	0.8
Medium	ForGW	True	Poor	0	0.2	0.8
Medium	ForGW	True	Medium	0	0.1	0.9
Low	ForDam	False	Good	0	0.05	0.95
All remaining combinations give probability:				0	0	1

Surface water resource	Ground water resource	Forest	Storage potential		
			One Year	Two Years	>Two Years
High	High	High	0	0	1
High	High	Low	0	0	1
High	Medium	High	0	0.5	0.5
High	Medium	Low	0	0.4	0.6
High	Low	High	0.1	0.5	0.4
High	Low	Low	0	0.6	0.4
Medium	High	High	0	0.2	0.8
Medium	High	Low	0	0.1	0.9
Medium	Medium	High	0	0.4	0.6
Medium	Medium	Low	0	0.3	0.7
Medium	Low	High	0.3	0.7	0
Medium	Low	Low	0.2	0.8	0
Low	High	High	0	0.3	0.7
Low	High	Low	0	0.2	0.8
Low	Medium	High	0.2	0.3	0.5
Low	Medium	Low	0.1	0.4	0.5
Low	Low	High	1	0	0
Low	Low	Low	0.9	0.1	0

Forest	Ground water resource	Surplus ground water	
		True	False
High	High	0.7	0.3
High	Medium	0.5	0.5
High	Low	0.1	0.9
Low	High	0.9	0.1
Low	Medium	0.8	0.2
Low	Low	0.1	0.9

Figure 13 Conditional probability table for 'water resources' (cont.)

Results of scenario testing and sensitivity analysis of main framework

Methodology

This framework was developed with the specific aim of integrating the main qualitative findings of the research into a reasonably objective framework where they could be analysed. Because the network is designed to model Patrick Moriarty's beliefs in the system which he has been studying, the results come as no surprise to him. What is important is that the framework is accessible to any other interested parties who will hopefully understand more clearly the logic behind these beliefs (expert opinions), and may question or argue with them.

Sensitivity analysis was done using the method described in Section 4.1. The analysis was used to identify the key variables effecting livelihood improvement and catchment management, following which the probable effects of carrying out a programme of catchment management within the Romwe catchment were investigated.

Important variables effecting livelihoods

Table 2 the relative importance of the 20 most important nodes in terms of their effect on livelihoods. Catchment management lies 12th in order of importance (there are 43 nodes in the network). The network clearly reflects the importance of arable farming systems, whose effect (as shown through the node ability to benefit from improved arable) is an order of magnitude more important than any of the other nodes.

Table 2 Factors affecting livelihoods

Rank	Node	Entropy Reduction
1	*Improved livelihoods*	0.528
2	Ability to benefit from improved arable	0.132
3	Increased use	0.032
4	Ability to intensify agriculture	0.027
5	Labour availability	0.012
6	Openness to new ideas	0.011
7	Surplus ground water	0.010
8	Improved soil water	0.010
9	Storage potential	0.010
10	Markets	0.009
11	Pressure on land	0.009
12	Ground water resource	0.008
13	Catchment management	0.006
14	Rainfall	0.005
15	Surface Water Resource	0.004
16	Physical Ability	0.003
17	Population	0.002
18	Donor	0.002
19	Community Cohesion Donor	0.002
20	Drive to intensify water use	0.002

The effects of entering a finding directly at *improved livelihoods* has the effect of reducing entropy by 0.528. This reflects the fact that the underlying probability for improved livelihoods is initially skewed – reflecting a belief in a general tendency of livelihoods to worsen in the absence of any action. The importance of entering other individual findings is therefore relative to this value, and not the maximum theoretical value of entropy reduction, one. The table therefore reports that, with the exception of *ability to benefit from improved arable*, the entering of findings at any *individual* node has little effect on livelihoods.

Main factors in determining likelihood of micro-catchment management being successful

To determine the potential importance of catchment management interventions on catchment water resources, a number of test scenarios were run through the DSS. Table 3 shows the results of the different scenarios on the quantity of ground, surface, and soil moisture respectively under different levels of catchment management. It is assumed that catchment management is optimised for the particular sector of the resource being modelled, i.e. when looking at groundwater management it is assumed that the '*type of SWC*' node is set to 'forGW'.

The table therefore shows the expected change that shifting from poor to good catchment management could be expected to give under different conditions of rainfall, and for different types of catchment management. For example, in an area of medium rainfall with poor catchment management focussed on groundwater there is a 5% chance of high groundwater availability, 25% of medium, and 70% of low. Shifting to good catchment management leads to a 50% chance of high groundwater, 30% probability of medium, and 20% chance of low. The table indicates under what conditions the various water types can be improved substantially by moving from poor to good catchment management. For groundwater, a sizeable improvement in supply can be achieved under medium rainfall conditions, but not under poor or good rainfall. For improved surface water and improved soil moisture, it is particularly under low rainfall conditions that it is worth moving from poor to good catchment management.

Table3 The effects of catchment management on water resources

			Poor Catchment Management			Good Catchment Management		
Resource sector	Resource state	Rainfall →	Low	Medium	High	Low	Medium	High
	High		0	5	65	7	50	85
Ground water	Medium		0	25	23	28	30	12
	Low		100	70	12	65	20	3
	High		0	20	50	0	20	40
Surface water	Medium		0	40	35	40	40	40
	Low		100	40	15	60	40	20
Improved soil	True		0	40	60	60	80	60
Moisture	False		100	60	40	40	20 40	

Important drivers to water resource development

Table 4 shows the effect in reducing uncertainty at the *ability to use water to intensify agriculture* (*ability*) node of findings from ten of the nodes listed in Table 2. Because of the BBNs ability to 'reason backwards' one of the nodes (marked *) is in fact a child of the *ability* node. This means that findings entered in *improved livelihoods* node have an effect on *ability to use water to intensify agriculture*, and so permit a user by entering a finding to see the most likely states of the parent node to have caused that finding.

Table 4: Main nodes effecting Ability to use water to intensify agriculture

		Entropy reduction
	Ability to intensify agriculture	*0.833*
1	Openness to new ideas and experiences	0.110
2	Physical ability	0.103
3	Land	0.049
4	Catchment Management	0.033
5	Labour availability	0.033
6	Improved livelihoods*	0.027
7	Community cohesion	0.027
8	Skills	0.015
9	Education/Aspirations	0.007
10	Equity of land distribution	0.005

As with other nodes examined earlier, no single node has the ability to effect a major reduction in the entropy of the *ability to intensify agriculture* node, reflecting the complex and interdependent nature of the system. However, two nodes which do have an effect an order of magnitude greater than the others are *openness to new ideas* and *physical ability* (itself a summary node). This reflects the importance of a community being receptive to the aims of the project (catchment management or other), and of having the requisite skills and capital to carry it out.

The utility of catchment management in the Romwe catchment

This section takes the knowledge gained by this and other projects carried out within the Romwe catchment and uses it to assess the probable utility of undertaking a catchment management project within the study area. Again it is emphasised, that in this case, the catchment management referred to is the portfolio of physical interventions only.

The Romwe catchment is in fact made up of two or three sub-catchments based on soil type and geology (Lovell et al, 1998). Each of these is assessed independently in addition to which the catchment is assessed as a whole. Findings are entered at the most appropriate level according to knowledge about the catchment. The findings entered for the catchment as a whole, and the three sub-catchments are listed in Table 5.

Table 5 Findings entered to nodes for the Romwe catchment and sub-catchments

Node	All Romwe	Deep red soils	Shallower soils	Duplex soils
Rainfall	Medium	Medium	Medium	Medium
Geology	CrystGneiss	N/A	N/A	N/A
Soil type	N/A	FDDeep	FDShallow	Duplex
Suitability for dam	False	False	False	False
Donor aid	True	True	True	True
Proportion forest	Low	Low	Low	Low
Supportive external environment	False	False	False	False
Extension	True	True	True	True
Previous experience	True	True	True	True
Community cohesion	True	True	True	True
Age profile	Young	Young	Young	Young
Equity of land distribution	False	False	False	False
Markets	True	True	True	True
Population density	Medium	Medium	Medium	Medium
Land available	True	True	True	True

Nodes with N/A entered for their state reflect the concept of d-separation discussed by Jensen (1996). Because *geology* acts on the rest of the network through *soil type*, the entering of a finding for *soil type* leads to *geology* becoming d-separated – that is unable to influence the rest of the network. Conversely, where data on soil type does not exist for the specific site, but geological information does, then entering a finding in the *geology* node will lead to the *soil type* node reflecting a spread of states according to the underlying CPT.

Table 6 Results from DSS for changing catchment management from bad to good

	Livelihoods improve	Poor catchment management ForGW	ForDam	ForSW	Good catchment management ForGW	ForDam	ForSW
All Romwe	True	22	22	21	36	29	20
	False	78	78	79	64	71	80
Deep red	True	25	25	20	40	33	18
	False	75	75	80	60	67	72
Shallow	True	24	24	24	36	31	18
	False	76	76	76	64	69	82
Duplex	True	14	14	18	26	19	25
	False	86	86	82	74	81	75

The results show clearly that for all soil types catchment management for groundwater will have the greatest impact on livelihoods (Table 6), however it is equally clear that nowhere is catchment management alone sufficient to raise the chances of improving livelihoods above 40%. Catchment management for a dam, which gives the second best results is misleading in this case as there is no suitable site for a dam within the catchment, it reflects the state in a Romwe like catchment where there is a suitable dam site. However, due to the structure of the network, good catchment management for a dam also has some positive effects on groundwater storage. In effect this node shows how a programme of catchment management that is well carried out but improperly targeted may still have a positive effect. The consistently low values seen for catchment management for soil moisture are largely driven by the findings that land distribution is inequitable and that there is little available labour for rainfed farming, thus attempting soil moisture improvemnets makes little impact on livelihoods overall. Setting these two nodes to 'high' values, i.e. where labour is not in short supply and where land is equitably distributed means that on duplex soils the probability of improving livelihoods would move from 25% (with labour constrained and inequitable distribution) to 37%. The generally low values for duplex soils reflect both their unsuitability from a physical point of view for groundwater based systems; and the social unsuitability of the Romwe catchment for arable farming interventions.

Importance of aspects of the problem domain to catchment management for improved livelihoods

This section returns to the groups discussed in the network narrative structure (Section 4.3) and examines the relative effect each group has on the functioning of the network. The results reported and discussed are based on tests carried out using the model and were similar to those discussed earlier in the paper.

Physical base and approach to catchment management

For catchment management to be worthwhile there must be a responsive physical base, and the catchment management approach must be tailored both to this base, and to a clearly defined sub-set of the water resource (ground, surface, or soil moisture). As developed the DSS suggests that catchment management for surface or groundwater will be most useful in areas of medium rainfall, with suitable soils. Areas in which rainfall is either very good, or very poor will show little response to management for surface or groundwater, but are likely to respond well to soil water conservation measures.

Physical ability to benefit from catchment management and improved water resources
Communities must possess certain attributes (referred to as 'physical' to distinguish them from 'institutional') in order to be able to benefit from improved access to water resources. These include their skills base, available land where this is a requirement, and a supportive external environment. Of particular importance is labour availability, which rather than determining absolutely whether catchment management is suitable or not will have an important conditioning effect on deciding which type of catchment management approach to adopt, particularly in deciding whether to focus on group or individual systems.

Social ability to benefit from improved catchment management and water resources
This examined the rôle of more nebulous, although crucial, information such as community cohesion, leadership, openness to new ideas and age profile. A crucial area, it is one of the most difficult to come to grips with, and in particular to model in any sort of quantitative manner. For this reason it is one of the sectors most commonly left out of traditional modelling analysis yet, as is shown in the network, is one of the most central to overall project success. This group is particularly important for deciding whether an individual or group approach should be taken to project development – communities with high population densities, and young populations are all likely to be more responsive to a communal approach, particularly where the community works well together, has good educational standards and is already well integrated into the cash economy. On the other hand older communities, where population pressures are not so high and where land access is fairly and evenly distributed, will tend to benefit more from an individualistic approach.

External drivers
A number of important external drivers were identified, which affect both the likelihood of overall project success, and the approach most likely to bear fruit. They include 'internal' factors such as equity of land distribution, population density, and overall access to land, and external factors such as the existence of a donor (in the sense of some sort of external agency capable of injecting capital and expertise and acting as a facilitator and catalyst). Again, varying combinations will tend to condition the approach most likely to be successful in different directions. For example, the absence of an external catalyst (regardless of whether capital is involved) will dramatically lower the chances of any 'communal' approach being successful, while having less effect on more individualistic approaches built around arable production.

Finally there are the effects of the country's or region's macro-economy, most importantly in how it affects access to jobs in cities, transport and, of paramount importance, markets. The existence of markets both local and regional) is perhaps the single most important catalyst to increased production and hence income.

Conclusions and the future

This paper has sought, through the medium of a decision support system developed using a Bayesian Belief Network, to draw together some of the main lessons of the research work reported in this study, augmented, where necessary, by expert opinion from other sources, within a single coherent framework to address the linked questions of water resource development and catchment management at a more generic level.

The use of BBNs for decision support and conceptual framework development

This section deals with the development and use of a BBN based DSS, its strengths and weaknesses and how the work might be carried forward in the future.

The use of a BBN to bring together the findings from the project and to move from a single case study to a larger framework for analysing catchment management and water resource management was a success. Flow diagrams are now the accepted way of showing in simple graphical format how systems work. However most stop at this level, giving an output which, while useful, is limited. BBNs by allowing a conceptual framework to be tested, and used to assess scenarios and hypotheses add a new dimension to this approach. If there is a danger, it is that too much weight may be put on outputs which are easy to generate and easy to understand but may in some cases lack meaning. However, there is no doubt that, for work that spans disciplines and integrates 'hard' and 'soft' science, they present one of the most promising ways forward.

The work reported in this paper is a case study; as such great care must be taken when trying to extend lessons from it to the wider world. The BBN framework developed on the basis of the output from the study, while useful in its current form for examining the conceptual limits of the problem domain (Section 3.1), is by itself insufficient to offer any but the broadest outlines as to how and where water resource and micro-catchment management projects might be carried out. To become a truly useful tool for project level decision support, this or similar frameworks would need to be joined to a knowledge base upon which clearer, 'harder' relationships between the nodes could be defined. Such a knowledge base was developed for the Romwe catchment, and used to support the development of relationships within another BBN (Moriarty et al, 1999b; Cain et al, 1999a). Nonetheless, the provision of a widely accepted analytical framework is a useful first step towards the development of a decision support system, and it is hoped that the output from this project may serve within such a context.

The role of belief networks in integrating small scale deterministic physical models with social and economic data

As was explained earlier the network developed above was intended as a framework for testing in a quasi-objective fashion qualitative findings from the catchment study. The network is a useful tool at this level, however it has drawbacks. Chief amongst these is the lack of 'hard' data underlying the conditional probability tables between the nodes. BBNs can integrate data from three principal sources: real data; expert opinion; and models. While expert opinion is often acceptable for defining important, but intangible elements of the decision support framework such as 'community cohesion' or 'leadership', it is less so for the harder relationships associated with the biophysical, and to a lesser extent the socio-economic worlds.

There is an ongoing and intractable debate between advocates of deterministic versus stochastic methods for 'modelling' within the biophysical sphere. However the reality for much of the developing world is that data sets are few and far between and frequently not particularly trustworthy (the Romwe catchment is a rare example of a monitoring project that has managed to escape the restrictions of the dreaded three year 'project cycle' and is moving towards having a data set that is long enough to be of some use). As a result the use of deterministic, process based models is largely unavoidable. Nonetheless there are serious problems linked to this approach, not least of which is the danger of losing sight of the frequently high degree of uncertainty underlying modelling outputs.

Bayesian belief networks can help to circumvent these problems by making uncertainty explicit. They can for example be used as high level 'meta-models' (Varis, 1998), integrating output from a number of different deterministic and stochastic methods, and assigning spreads of uncertainty to the values thus elicited. Equally, they may be used to integrate conventional sensitivity analysis from a single model, with parameters being varied across the expected range, and the output being integrated into the conditional probability tables of a BBN.

The conceptual framework for the catchment intervention could have modelling input in a number of places. For instance incorporating data from climate change models could support the rainfall, rainfall cycle and climate change nodes. A deterministic catchment model such as ACRU could be used to provide data on the interactions between type of soil and water management, proportion of forested land, rainfall and water resources. Hard (or modelled) data on the links between job availability in cities, markets and the macro-economy could also be incorporated and so on. However before taking steps towards collecting new data it is important to evaluate the likely decrease in uncertainty that will be gained, and to then weigh this against the likely cost of acquiring the data. While this is perhaps not relevant within the context of a scientific study, it is highly important within the real world context of decision making under uncertainty for development issues, and again a sphere in which BBNs can give great support.

There is already a huge body of research work in both the 'black' and 'grey' literature, much of it mouldering away upon the shelves of ministries in various countries (Adams, 1992). Before carrying out yet more 'original' research there is need to consolidate what has already been done. Within this context BBNs offer an exciting new way of bringing together very disparate data sources within useful frameworks, which could then be used not only for decision making about development needs, but also to target better the next generation of research.

Broadening the definition of micro-catchment management

For the sake of testing and demonstrating the network developed in this paper, a very narrow definition of micro-catchment management, relating purely to physical interventions, was used. This was justified in terms of the need to highlight and demonstrate the effects of trade-offs between the different approaches to micro-catchment management. However it was clear from the results that physical catchment management on its own is incapable of having a major impact on peoples' livelihoods other than within a very narrow range of parameters.

It was clear that a number of both external and internal factors effect a community's ability to improve its livelihoods far more than the possible improvements in water resource availability brought about by improved micro-catchment management. This is not to say that the framework provided by the BBN is not useful; it helps to quickly and clearly identify both the narrow range of existing parameters where physically based micro-catchment management can be potentially useful and, where these do not exist, helps to highlight their limitations. By broadening the definition of micro-catchment management to (more realistically) include social, institutional, and economic factors - for example through partnership with a local authority to provide an enabling environment – the BBN can help to produce a package of interventions tailored to the specific needs of a given community and catchment.

Micro-catchment management as a management paradigm

Section 6.3 above suggests that with a broader understanding of what is meant by micro-catchment management the network developed could act as a useful tool in implementing a micro-catchment management programme. However, at a higher level, the question remains as to whether micro-catchment management is the optimal management paradigm when compared to *other* potential or existing ones. The DSS was designed primarily to assess on a case by case basis whether an area was likely to benefit from a physical micro-catchment management approach; other likely constituents of a good micro-catchment management programme, institutional strengthening, extension, training and so on were left out of the equation. This is because these factors should form part of *any* natural resource management programme. The BBN focuses on those aspects specific to a catchment based approach; in other words interventions designed to have a specific impact on water resources.

The suggestion of the DSS is that, in the vast majority of cases, the decision as to whether or not to take a physical catchment management approach has a negligible impact on water resources and even less on livelihoods. In relative terms a number of factors both extraneous (wider economy, underlying geology), and internal (cohesion, education) to the community rank equally or more highly in terms of general impact on well being.

While the network does not attempt to model the cost-benefit of taking a physically based micro-catchment management approach as compared to remaining with existing NRM strategies, the costs of such a change are likely to be high. The findings from the BBN do not suggest that the benefits are generic enough to merit a wholesale adoption of a micro-catchment based approach to management. Instead they show that that micro-catchment management should become a part of wider natural resource management portfolios, available to be used when the setting is right, and genuine benefits are to be gained.

Final comments

In general the approach of using a BBN as a framework within which to bring together knowledge from the Romwe catchment case study, has been successful. Even at the relatively simple qualitative stage to which it has been developed, the BBN provides a useful framework for examining and testing ideas about catchment management. The fact that the framework is accessible to all actors in a multidisciplinary project, and calls for no specialist knowledge to understand or manipulate, makes it a powerful tool for interdisciplinarity and consensus building both within a management team and in the wider community. While BBNs are a relative newcomer to the field of natural resource management they are set to play an increasingly important role.

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