Catchment Hydrology and Sustainable Management (CHASM): an integrating methodological framework for prediction

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Abstract New predictive methodologies are needed to support sustainable catchment management, particularly in poorly gauged or ungauged basins. The CHASM research programme has been established to gain new understanding of the hydrological and ecological functioning of mesoscale catchments (10^2–10^3 km^2) and of how catchment response changes with scale, and to translate this new knowledge into enhanced predictive capability. In the UK, four mesoscale catchments are being instrumented at the patch/hillslope, micro-catchment (1 km^2) and mini-catchment (10 km^2) scales. A Generic Experimental Design (GED) involving the use of Permanent, Staged and Mobile Instrumentation is being employed to capture the heterogeneity in catchment response across this range of scales. The GED forms part of an Integrating Methodological Framework in which field experimentation and monitoring is linked with landscape classification, modelling and prediction in an iterative cycle in which experimentation is steered by the reduction of predictive uncertainty. The implementation of the CHASM approach on a global network of mesoscale basins would make a significant contribution to achieving the goals of PUB.

Key words catchment; experimentation; mesoscale; modelling; prediction

RATIONALE AND KEY ISSUES

Across the globe, water resources and water environments are under threat as never before. In river basins everywhere, Man's activities have disrupted the natural hydrological and ecological regimes. Impacts are felt not only locally, but are transmitted through land–surface feedbacks to disturb the climate itself. Water supplies are no longer secure, flood risk is perceptively increasing, and biodiversity is threatened. The challenge is to identify appropriate responses to these threats. Sustainable management policies are needed to provide water, not only for life, health and development, but to prevent further ecosystem degradation. New predictive methodologies are needed to support sustainable management, particularly in poorly gauged or ungauged basins.

Progress in developing the science base needed to underpin the sustainable management of catchments has been inhibited by the fragmentation of research effort, and a failure to develop an integrated approach to experimentation, modelling and prediction. Experimentation has been largely confined to small headwater catchments, typically less than 10 km^2, and it has not generally been possible to extrapolate the results of these experiments to larger ungauged areas. Moreover, small-scale process experimentation has not been undertaken within a framework which enhances understanding of overall water cycle functioning at the catchment scale. On the other hand, sustainable management issues must be addressed for catchments with areas greater than 10^2 km^2, within which water must be stored/abstracted for supply, polluting discharges diluted or conveyed to the sea and wetland habitats and migratory fish populations preserved. While numerous decision support systems have been constructed to support the management of such catchments, these systems are often scientifically hollow. This is because the models which underpin these systems have not been developed from a basis of scientific understanding of hydrological cycle functioning at a range of catchment scales, but from the basis that one must "make do" with the available data, and somehow calibrate the available model(s) and use them for prediction without proper recognition of the associated uncertainties. This is particularly true when predicting the impacts of environmental (climate, land-use) change.

There are a number of issues which arise from the above considerations:

(i) the databases for larger catchments are wholly inadequate to support scientific research which can enhance the understanding of how these basins function, and of how environmental change may impact them;
(ii) the models, and their predictions, are not generally fit for purpose, and their capacity to predict the responses of ungauged basins under current climatic conditions, never mind future conditions, is unknown. Consequently, prediction at ungauged sites still relies on empirical techniques such as regionalized unit hydrographs and flow duration curves which cannot meet today's needs.

While there is extensive literature on catchment modelling, and a diversity of approaches, little genuine progress has been made in recent years in delivering improved predictive capacity. Moreover, much of the modelling activity has lacked a clear focus, and no clear signposts have emerged for end users on how models might be used to support sustainable management. However, there has been an increasing awareness of the need to recognize and quantify predictive uncertainty, but we are lacking protocols for conducting intensive field campaigns to provide data to reduce the uncertainty.

In the UK, a consortium of universities and research institutes was formed in 1998 to launch the CHASM initiative in catchment research. National funding of £2M has been obtained from the UK Natural Environment Research Council (NERC) to instrument four mesoscale catchments (~10^2 km^2) representing a range of climatic conditions, physical characteristics and anthropogenic impacts. Mesoscale catchments play a key role in determining the functioning of larger basins, and are frequently the major sources of runoff for water supply. A Generic Experimental Design has been developed which facilitates the coherent sampling across catchments of the spatial variability in hydrological, geomorphological and ecological responses. This new infrastructure is supporting an integrated experimentation, modelling and prediction approach in which field experimentation and data capture are driven by the reduction in predictive uncertainty, and which will provide the scientific understanding and predictive capacity needed to underpin the sustainable management of UK catchments, gauged and ungauged.

Five Key Issues have been identified which will drive the CHASM research programme:

(1) The vast majority of catchment experiments have been conducted at the microscale (<10 km^2), only limited aspects of hydrological understanding can be transferred to larger scales (the scale issue).

(2) The range and intensity of anthropogenic influences within catchments is increasing and impacts are not fully understood, particularly in relation to ecological diversity and biogeochemical cycling.

(3) A better understanding is needed of how catchments are likely to behave under future climate conditions.

(4) The damage caused by natural hazards (floods, droughts, landslides, etc.) is increasing, and the controlling mechanisms need to be better understood.

(5) Sustainable management plans for catchments need to be underpinned by good scientific understanding, particularly of the influences of abstractions on the hydrological and ecological regimes of catchments.

Key Elements of the CHASM research programme include the following:

- a new focus on mesoscale catchment research to bridge the gap between the typical scale of past experimental catchment research (~10 km^2) and the catchment scales which are the focus of sustainable management issues;
- a major assault on the scaling issue, with new scaling theories to be developed and tested using multi-scale experiments;
- a set of *n* mesoscale nested catchment experiments which (a) sample heterogeneity in rainfall/topography/soils/vegetation/geology comprehensively, and (b) cover a range of anthropogenic impacts;
- an integrated monitoring and modelling approach in which modelling is used from the outset to design the catchment experiments and to steer field campaigns;
- an improved scientific basis for prediction in ungauged catchments;
- a scientific platform for new developments in hydroecological research.

DEVELOPING A STRATEGY FOR INSTRUMENTING MESOSCALE CATCHMENTS: THE GENERIC EXPERIMENTAL DESIGN

Strategy

To gain new understanding of the hydrological functioning of mesoscale catchments for a finite budget, there are essentially two choices:

(i) instrument one mesoscale catchment intensively (e.g. gauge most/all of the sub-basins: Woods *et al*., 2000), leave the instrumentation in place for several years, and hopefully gain a full understanding of the hydrological, geomorphological and ecological functioning of that catchment;

(ii) instrument a number of mesoscale catchments using a sampling strategy, and thereby cover a wider range of climate/soils/vegetation/geology/geomorphology.

The difficulty with approach (i) is that no two mesoscale catchments are similar and there is the difficulty of extrapolating the understanding gained to other catchments. While approach (ii) will not provide complete sampling of the variability in response within any one catchment, it can help to understand why there are differences in responses between catchments, which can be more important in extrapolating the results to other mesoscale catchments. Approach (ii) has been taken in instrumenting the four CHASM catchments, and a Generic Experimental Design (GED) has been developed to maximize the information gained on the space–time variability of surface and sub-surface responses across the catchment. The GED is characterized by measurements taken across a range of scales, and involves an adaptive "staged" approach to understanding and resolving the significant spatial variations in hydrological/geomorphological response. The key steps involved are:

(i) landscape classification;
(ii) an adaptive staged approach to instrumentation involving: mobile instrumentation; permanent instrumentation; staged instrumentation;
(iii) a multi-scale approach with a nested structure;
(iv) understand and resolve heterogeneity (through integrated monitoring and modelling);
(v) re-classify the landscape, and repeat the cycle.

The experimental design is seen as an iterative process in which the effects of heterogeneity in topography, soils, vegetation and geology on catchment response are understood and resolved, leading ultimately to the classification of the landscape into hydrologically homogeneous domains.

Landscape classification

Digital maps of topography, soils, vegetation and geology are, in the first instance, being used together with *a priori* knowledge and understanding of the dominant controls on hydrological response to produce a first attempt at landscape classification. It is recognized that any classification scheme must reflect a specific purpose which, in the case of catchments, can be defined in terms of hydrological, geomorphological or ecological response. Permanent, Staged and Mobile Instrumentation are being deployed in accordance with this initial classification. As data become available and models are developed, the understanding of the controls on hydrological response will be enhanced, leading to the reclassification of the landscape and the redeployment of instrumentation to sample unresolved hydrological variability.

Mobile instrumentation: the Green Machine

The "Green Machine" (e.g. Tyndale-Biscoe *et al.*, 1998) is an all-terrain vehicle that has been adapted to carry out rapid surveys in the field (see Fig. 1). It is fitted with a

Fig. 1 The Green Machine.

high resolution, real time, Global Positioning System, a set of geophysical surveying equipment (including a ground conductivity meter and a seismic refraction kit) and a drilling rig. A number of geophysical experiments are envisaged that will work in tandem with the staged and permanent instrumentation. The Green Machine is being used in the initial land classification scheme to survey prospective instrumentation sites to ensure that those sites meet with the GED criteria. The vehicle will also be used for the installation of field equipment (using the drilling rig) and for downloading data loggers directly onto an onboard computer.

Mobile instrumentation: X-band radar

A mobile X-band radar similar to that deployed in the MARVEX experiment in New Zealand (Woods *et al*., 2000) will also be used within intensive field campaigns. This will provide high resolution information on the space–time variability of rainfall which will be used to study how the catchment integrates this variability as scale increases.

Permanent instrumentation: multi-scale approach with a nested structure

Permanent instrumentation will be positioned within each catchment to follow a multi-scale nested structure consisting of microscale (1 km^2) and miniscale (10 km^2) catchments (see Fig. 2). A major objective of CHASM is to scale-up process representation and catchment variability to the mesoscale. Miniscale catchments are seen as a key scale for observing the effect of local variability, but also to study mixing and attenuation processes. The microscale catchments will help to resolve spatial variability in responses, by monitoring processes within distinct land units as defined from the basic landscape classification scheme.

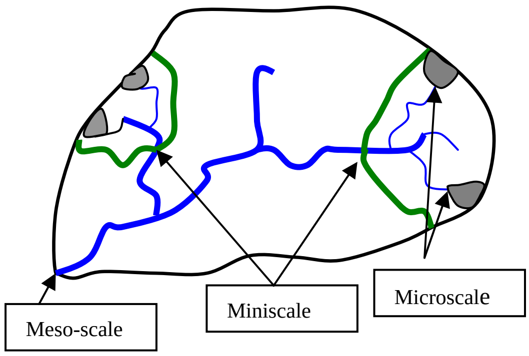

Fig. 2 Multi-scale nested structure for permanent instrumentation.

Staged instrumentation

Initially a series of detailed point scale measurements will be made within the microscale catchments (see Fig. 3). A dense network of logged instrumentation will generate the basic data needed to establish the mean and distribution of key hydrological variables, such as the water table dynamics, the soil moisture regime and the evaporative dynamics, for a patch of land approximately 50 × 50 m in extent. Patch instrumentation will improve the representation of catchment variability by targeting the heterogeneity seen at the hillslope scale. Two to three patches will be implemented on hillslopes within a microscale catchment to capture this heterogeneity. As this will require a large number of instruments, a staged instrumentation approach has been adopted. Firstly, a full set of instruments is installed, which are left to record data whilst other patches are implemented. The data from the instruments will be analysed frequently until it is agreed that the mean hydrological behaviour of the patch has been established. At this stage, several instruments that represent the mean behaviour of the patch will be left *in situ*, and the remainder used to establish patches in new microscale catchments. This approach is pursued until the microscale catchment heterogeneity has been resolved.

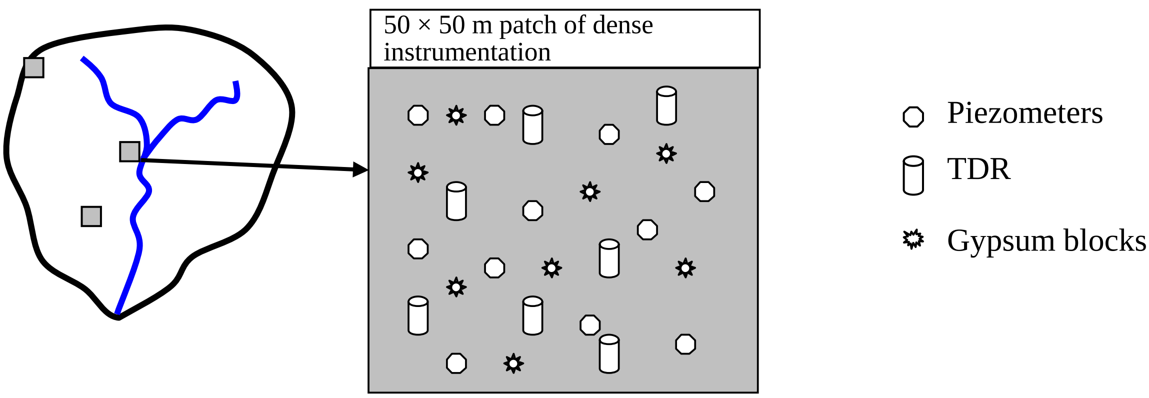

Fig. 3 Staged instrumentation within a microscale catchment and the use of patches to capture hillslope-scale variability.

IMPLEMENTATION OF THE GENERIC EXPERIMENTAL DESIGN

An Experimental Design Task Force has been set up to oversee the implementation of the GED, which is currently being implemented on the four mesoscale catchments, which are located in England (upper Eden 337 km^2), Northern Ireland (Oona, 92 km^2), Scotland (Feshie 200 km^2), and Wales (upper Severn 187 km^2) (Fig. 4). In choosing these catchments, account was taken of the previous existence of instrumented micro-scale catchments which could be incorporated into the GED. Responsibility for the different catchments has been allocated among the consortium partners, and Catchment Management Committees have been established to manage the catchments, take on board key issues from local stakeholders, and liaise with landowners and the public.

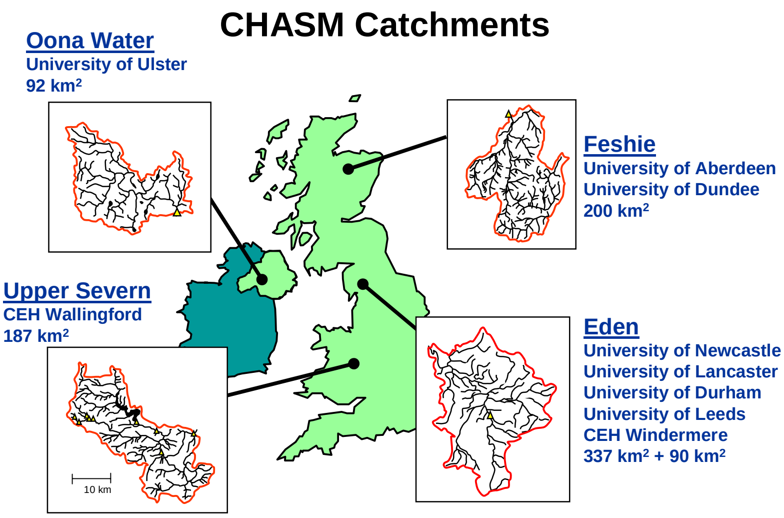

Fig. 4 Locations of the selected catchments.

Table 1 Structured approach to site selection.

Tasks	Instrument sites Mini-catchment 1	Mini-catchment 2	Mini-catchment 3	Groundwater monitoring	River flow gauges	Raingauges/met stations	Ecological monitoring
(1) Prelinary catchment landscape classification	Report on landscape classification						
(2) Define criteria for site selction (including use of landscape classification)	List of criteria	List of criteria	List of criteria	List of criteria	List of criteria	List of criteria	List of criteria
(3) Desk studies: analysis of existing data, maps, and previous studies	(ranked) list of potential sites	(ranked) list of potential sites	(ranked) list of potential sites	(ranked) list of potential sites	(ranked) list of potential sites	(ranked) list of potential sites	(ranked) list of potential sites
(4) Field visits	A report on each field visit						
(5) Multi-ciriteria analysis	(ranked) short-list of potential sites	(ranked) short-list of potential sites	(ranked) short-list of potential sites	(ranked) short-list of potential sites	(ranked) short-list of potential sites	(ranked) short-list of potential sites	(ranked) short-list of potential sites
(6) Interim reports	Interim report	Interim report	Interim report	Interim report	Interim report	Interim report	Interim report
(7) Site surveys using Green Machine to confirm choice of selected site(s)	selected site(s)	selected site(s)	selected site(s)	selected site(s)	selected site(s)	selected site(s)	selected site(s)
(8) Final reports	Final report	Final report	Final report	Final report	Final report	Final report	Final report

A structured approach to site selection has been adopted to ensure that the selected sites are, as far as possible, consistent with the overall GED. The steps involved in this process are summarized in Table 1. This will ensure that there is a documented audit trail for all selected sites, so that the rationale for specific choices is clear. In choosing sites, there are many practical constraints, and variations to the GED may eventually become necessary because of lack of access to first choice sites. The Foot and Mouth epidemic in the UK has created major access problems, and delayed installation of instrumentation by at least a year. It was expected that all of the instrumentation would be in place by the end of the summer of 2004.

INTEGRATING METHODOLOGICAL FRAMEWORK FOR PREDICTION

An Integrating Methodological Framework (IMF) is being developed which links multiscale experimentation with catchment/river classification, the multiscale modelling of environmental flows (water, sediments, nutrients) and the value of data in scale-dependent prediction of environmental flows (Fig. 5(a)). This framework involves an iterative cycle in which field experimentation is driven by the reduction in prediction uncertainty. How, what, and where to sample for different applications are key questions which will be investigated within this iterative cycle.

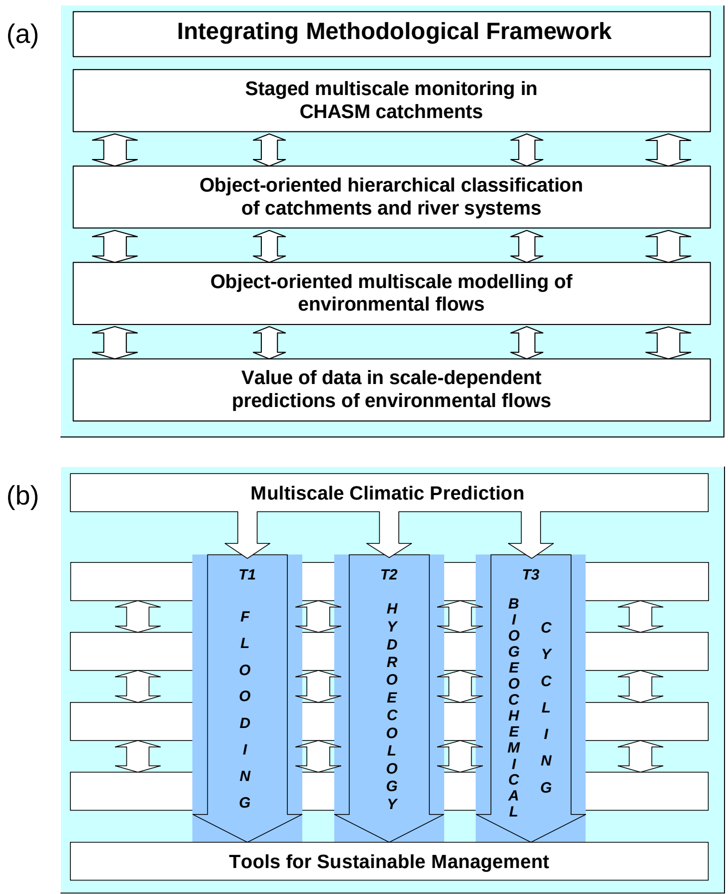

Fig. 5 Integrating Methodological Framework and research themes.

The Generic Experimental Design approach described above will be used to implement Staged Multiscale Monitoring in CHASM catchments. Catchments and river systems will be classified using an object-oriented approach in which the classification scheme adopted will relate to the object of prediction (e.g. a location where flooding can occur). Different classification schemes will be adopted for different applications. The object-oriented modelling of environmental flows (Fig. 5(a)) will involve the linking of model elements reflecting landscape/river system classification. This will be achieved through a Virtual Modelling Laboratory which will facilitate the construction of high-resolution virtual catchments for hypothesis testing, and the object-oriented linking of flow, sediment and biogeochemical models.

High resolution digital data which describe the main physical features of the landscape (topography, soils, vegetation, geology/geomorphology) are now becoming widely available, and spatially-distributed process-based modelling must be developed into a tool which can be used for routine prediction. However, the role of field experimentation and monitoring in constraining and reducing predictive uncertainty is critical to the successful use of such models. The value of data in scale-dependent predictions of environmental flows (Fig. 5(a)) is therefore critical to establishing the “fitness for purpose” of a model for a particular application, and the IMF aims to create a culture in which field experimentation is considered as a necessary adjunct of a model application if the uncertainty in predictions is to be reduced. This will involve the use of short intensive field campaigns (e.g. involving a Green Machine, tracer experiments, etc.) to reduce predictive uncertainty for ungauged catchment areas.

The Integrating Methodological Framework (IMF) will underpin research in three cross-cutting thematic areas: Flooding, Hydroecology and Biogeochemical Cycling (Fig. 5(b)). The climatic drivers for the thematic research will be provided through Multiscale Climatic Predictions which will focus on two areas: (i) the use of mesoscale atmospheric models for reconstructing meteorological variables from atmospheric re-analysis data, and validation using observed data (main context is ungauged or poorly gauged catchments); and (ii) the development of ensemble approaches to GCM downscaling using both dynamic and statistical approaches. Therefore, climatic inputs representing present and future climates will be provided.

Research under the Flooding Theme will, through field studies and model simulation experiments, identify the key controls on flooding and flood frequency curves in CHASM catchments. This will inform the development of a new, physically-based flood risk estimation framework which will be used to assess flood risk under climate change and land use/land management scenarios. Under the Hydroecology theme, research will focus primarily on physical river habitats, and how these change with scale. The hydraulic regime and substrate conditions of habitat patches will be predicted as a function of the river reach dynamics, flow and sediment regimes, and the impacts of environmental change on habitat mosaics and their substrate conditions assessed.

Research under the Biogeochemical Cycling theme will establish the hydrological controls on nutrient and carbon cycling in CHASM catchments, and how these change with scale. Nutrient and carbon cycling models will be linked to hydrological models to account for the controls, and the impacts of environmental change on nutrient and carbon cycling and transport will be predicted.

The Tools for Sustainable Management (Fig. 5(b)) will include:

(i) a Decision Support System (DSS) for assessing the ecological status of mesoscale catchments, under alternative socio-economic (land-use) and climate change scenarios;

(ii) a DSS for flood risk estimation and mapping, under alternative socio-economic and climate-change scenarios;

(iii) a DSS which can support the management of nutrient and carbon budgets in mesoscale catchments, under alternative socio-economic and climate-change scenarios.

Each DSS will consist of a range of decision support tools, ranging from simple sustainability metrics through risk matrices to the use of full model-based scenario analyses.

ROLE OF CHASM IN PUB

To make a major impact on prediction in ungauged basins in the coming decade, new theoretical developments on the scaling of hydrological responses are needed. These will need to be supported by catchment experiments in the different climatic zones which are executed within a unified methodological framework. This framework must incorporate a common experimental design which can support the development and testing of new scaling theories. The CHASM Integrating Methodological Framework indicates how this can be approached for mesoscale catchments. Historically, many experimental and representative basins have been established throughout the world, but no attempt has been made to adopt a common multiscale experimental design in these catchments. It is hoped that coordinated experimentation, modelling and prediction in mesoscale catchments can be extended globally within the framework of PUB, since this can provide an important contribution towards achieving PUB goals.

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