THE HYDRAULICS OF PHYSICAL BIOTOPES - TERMINOLOGY, INVENTORY AND CALIBRATION.

REPORT OF A WORKSHOP HELD AT CITRUSDAL 4-7 FEBRUARY 1995

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1. PARTICIPANTS

J.M.King: Principle Scientific Officer with the Freshwater Research Unit (FRU), Zoology Department, University of Cape Town. Dr King has twenty years of experience in South African river ecology and is the representative for the rest of the country on the Kruger National Park Rivers Research Programme (KNPRRP). Together with Ms R. Tharme, Dr King has assessed the Instream Flow Incremental Method (IFIM) for South Africa and is involved in developing alternative approaches to instream flow assessments for this country. She is currently employed on a Water Research Commission (WRC) contract investigating the ecological significance of low flows.

G.McGregor: Masters student, Department of Geography, Rhodes University, Grahamstown. Ms McGregor is working on a thesis investigating the geomorphological impacts of impoundments. She acted as transcriber during the workshop.

M.D.Newson: Professor of Physical Geography and a Director of the Centre for Land Use and Water Resources Research, Department of Geography, University of Newcastle upon Tyne. Professor Newson has over twenty five years of experience in the practice of hydrology and geomorphology. Before joining the University of Newcastle upon Tyne he worked for 16 years with the Institute of Hydrology, U.K. He continues to work closely with the National Rivers Authority, being a member of the Technical Group for River Habitat Surveys and an R&D contractor for the project on the geomorphological typology of rivers in England and wales.

J.H.O'Keeffe: Director, Institute for Water Research (IWR), Rhodes University. Dr O'Keeffe has experience of a wide range of South African rivers, having worked in the field of river ecology in South Africa for the past ten years. Amongst other activities, together with Dr King he is a key member of the Department of Water affairs and Forestry's (DWAF) Instream Flow Requirement (IFR) workshops and serves on the management committee of the Kruger National Park Rivers Research Programme, being the manager of the Water Quality sub-programme.

K.Rowntree: Senior Lecturer, Department of Geography, Rhodes University, Grahamstown. Dr Rowntree has researched and lectured in the fields of hydrology and geomorphology for the last twenty years and has worked in England, Kenya and South Africa. She has been involved for the last three years in a WRC funded project developing a geomorphological classification system for South African rivers. She has acted in a professional capacity advising on the geomorphological aspects of Instream Flow Requirement (IFR) exercises.

W.S.Rowlston: Deputy Chief Engineer, Department of Water Affairs and Forestry (DWAF), Pretoria. Mr Rowlston has developed a research interest in the hydraulic modelling of low flows in rivers, particularly in respect of the determination of IFRs for ecosystem maintenance. He is also interested in integrated catchment management as both a modeller and a manager. Mr Rowlston has been involved in a number of IFR exercises, has developed an artificial stream for the IWR, Rhodes University and is a member of the Kruger National Park River Research Programme.

R.Wadeson: Junior Research Officer, Department of Geography, Rhodes University. Mr Wadeson is employed on the WRC geomorphological classification project and is registered as a PhD student. His thesis focuses on the development of the biotope concept as a means of describing ecologically relevant instream environments.

2. EXECUTIVE SUMMARY

The workshop brought together researchers and practitioners from the related fields of fluvial geomorphology, hydraulic engineering and stream ecology, providing the opportunity for a discussion focusing on the meeting point of the three disciplines. We were fortunate to have with us Professor Malcolm Newson, a fluvial geomorphologist/hydrologist from the Department of Geography, University of Newcastle upon Tyne, U.K., who has been involved in programmes similar to our own Instream Flow Requirement assessments. Hence not only could we pool the experience from a number of disciplines, but also from two different hemispheres.

All workshop participants have been involved in advising on river management in general and in the assessment of instream flow requirements in particular. Experience from all groups pointed towards the use of the physical biotope as an appropriate scale for modelling the hydraulic response of channel systems in a way that has ecological significance. As defined by Wadeson (this publication) the physical biotope is a spatially distinct in-stream flow environment characterised by specific hydraulic attributes. Different biotopes are associated with particular morphological units, but are stage dependent. The workshop was convened specifically to address the biotope concept and to explore its potential application to instream flow assessments.

The Instream Flow Incremental Method ology (IFIM) and its hydraulic/habitat model PHABSIM II have been used in the USA as a tool for assessing IFRs and are advocated by the National Rivers Authority (NRA) of England and Wales as one set of tools within a suite of management options. Its potential in South Africa has been tested by Dr King and Ms Tharme. Serious reservations about the use of IFIM to assess IFRs have been voiced by both Dr King and Ms Tharme and by Prof Newson. Both groups have suggested a simpler approach based on what is essentially the biotope concept.

The workshop began with a presentation by Dr King who gave a critique of IFIM/PHABSIM II. All participants then presented starter documents which outlined their research or experience relevant to the topic. Field trips and structured discussion followed over a two and a half day period.

The starter documents provided a review of the current status of research and management approaches that had some bearing at the biotope level. In her critique of IFIM/PHABSIM II, *Dr King* reviewed the negative and positive aspects of the method. PHABSIM II has the advantage over most hydraulic models of simulating cell-by-cell hydraulic conditions across a transect, but extrapolation to wider areas and linking biotic responses to changing discharge are both fraught with problems. For instance there are many kinds of rivers where PHABSIM II cannot be used successfully because of complex hydraulic conditions, the PHABSIM II output only predicts how much suitable habitat will be available at any discharge, not how it would be used (i.e it does not predict biotic response), and the PHABSIM II output appears to be interpreted wrongly in all scientific papers seen to date.

Professor O'Keeffe gave an overview of environmental research on South African rivers and examined the relevance of the biotope concept when applied to different scales of problem. He argued that it had more relevance to water quantity than to water quality assessments, but stressed that interpretation of habitat related impacts was gravely hampered by a lack of basic research on lotic ecosystem functioning. Assessment of lotic ecosystem integrity requires an integrated approach at a number of scales, of which the biotope may be one, but reach and catchment scales are probably more important. Professor O'Keeffe stressed the need for further research addressing catchment-channel interactions and the importance of making research relevant to the needs of communities who make use of the rivers.

The biotope concept was defined by *Mr Wadeson*. He described the biotope as the smallest unit in an hierarchical catchment classification. It provides the link between morphological units and flow hydraulics which determine the physical habitat for stream biota. In his paper Mr Wadeson explained how hydraulic indices such as the Reynolds and Froude numbers can be used to characterise biotopes over a range of spatial scales and through time.

Mr Rowlston described how, as an hydraulic engineer, he became involved in ecological studies. He discussed the different needs and approaches relevant to engineering and environmental applications. The hydraulics of low flows have a particular environmental significance: these require sensitive modelling. Mr Rowlston also criticised PHABSIM II and pointed to the advantages of modelling at the cell level. He also outlined the problems associated with modelling channels with high roughness elements; these are the flow environments that usually support the highest numbers and diversity of instream biota. He also mentioned the need to take bed mobility into account when modelling flow hydraulics, an aspect not considered by PHABSIM II.

The problem of selecting representative reaches and extrapolation from sample sites to larger areas was addressed by *Dr Rowntree*. Hydraulic modelling for IFR assessments is carried out at the scale of the cross-section, that is at the scale of the morphological unit and biotope. Within the IFR approach, selection of representative sites and extrapolation both imply the application of some kind of classification framework. The problems of classifying river systems and their components was discussed in relation to the great diversity which exists both within one drainage system and between separate systems due to their unique geographic locations. An hierarchical framework for river description was proposed as an alternative to a formal classification. Its application to reach selection and extrapolation was discussed.

In her second presentation *Dr King* described one South African approach to instream flow assessment. The approach, which is being developed as a joint initiative between DWAF and participating scientists, has been termed theBuilding Block Methodology (BBM). It is based on a workshop approach utilising readily available data and the best available knowledge and expertise. In this method the choice of representative sites is based partly on geomorphological criteria. Hydraulic modelling is based on detailed surveys across morphological units that are deemed ecologically to be either representative or critical. Riffles are often chosen as critical units due to their relevance as hydraulic controls in hydraulic modelling, and because they are usually the first areas to dry out as discharge falls, and thus act as `warning beacons' for deteriorating conditions. Dr King described the information requirements for each cross section. Some of the information is collected in the field, some derived from hydraulic simulation. Dr King stated the need for further insight into geomorphologically important flows; that is the channel maintenance flows which achieve most work in terms of sediment transport, bed scour and bank erosion.

Professor Newson spoke to a paper co-authored with Ms Catherine Padmore and Mr M Charlton of Newcastle University. He described a study that is being carried out in the north east of England investigating the hydraulic characteristics of a range of morphological units. The work closely parallels that of Mr Wadeson in South Africa and the convergence in results is notable. As with the South African work, the dynamic nature of biotopes was stressed. Their present methodology focuses on morphological units within isolated reaches, but Professor Newson suggested that if the approach can be extrapolated or synthesised for whole river systems it may be developed as an economical alternative to PHABSIM II.

The discussion which followed the starter papers centred on three groups of questions:

1. What is the ecological significance of a biotope? Is it an appropriate scale for studying ecological structure and functioning ?

2. Is the biotope best identified by hydraulic conditions, specifically flow type ? How can substrate be incorporated?

3. How should representative sites be selected and how can we extrapolate from one site to another?

Field visits to sites on the Olifants River and its tributaries served to focus discussion on practical problems of biotope identification and site selection.

An important achievement arising from the discussions was the adoption of a common terminology relating physical biotope to flow type. This was summarised by means of a `biotope matrix'. Further research is needed before this relationship can be placed within the framework provided by the channel morphology.

It will also be necessary to confirm the ecological significance of identified physical biotopes. A clear need was expressed for co-operative research between geomorphologists and ecologists.

The present document represents the results of an intensive four day workshop in which a number of ideas from several researchers crystalised out of a common melting pot. Many of these ideas need to be tested further, so that the report must be seen as part of a longer term building of linkages between geomorphologists, hydraulic engineers and ecologists. We hope that the document will raise further discussion on the development of concepts, definitions and techniques.

ACKNOWLEDGEMENTS

Both the workshop and Professor Newson's visit to South Africa were funded by the Water Research Commission. The Department of Water Affairs are to be thanked for supporting the attendance of Mr Rowlston. Both parties are to be thanked for their contributions and for permission to publish the proceedings.

3. STARTER PAPERS

3.1 CRITICAL ASSESSMENT OF IFIM

Jackie King, Freshwater Research Unit, University of Cape Town

The following is a summary of conclusions drawn from a three-year project, the major portion of which was spent learning the Instream Flow Incremental Methodology. The report on that project appears as Water Research Commission Report 295/1/94, authors Jackie King and Rebecca Tharme.

NEGATIVE ASPECTS

1. IFIM is extremely complicated in concept, because it draws together ideas and techniques from many different disciplines. It is made more difficult to understand and apply by the fact that there is no clarity from its authors on which parts are practical, tested guidelines and which are still at conceptual, untested levels. Further, there has been minimal `housekeeping' of its model PHABSIM II as the methodology has evolved, and so new users, or those geographically isolated from its main area of application (North America), can be confused by parts of it that are redundant or invalid, or not pointed out as being designed for very specific purposes (eg. flows required for canoe passage).

2. The `macrohabitat' part of the methodology could not be applied in its entirety. Essentially this part is designed to extend the PHABSIM II (hydraulic/geomorphological) prediction of available habitat in the reach represented by the cross-sections, to the wider picture of how much the TOTAL physical habitat may have changed within the entire study area, when predicted changes in variables such as water quality and temperature are included. We found this difficult to do.

- Firstly, representative geomorphological reaches for the hydraulic simulations may not (probably will not!) coincide with major changes in water temperature, chemistry and so on, so one needs to understand the limit of what a PHABSIM II representative reach is: it represents a length of river over which the PHABSIM II hydraulic simulation can validly be extrapolated and nothing more. Representative reaches in terms of water chemistry or temperature may cover quite different areas; indeed, there are severe limitations to what they also can represent.

- This is because there is no guarantee that the biota is reacting to major changes in water chemistry and other macrovariables: a one degree increase in temperature may make all the difference to survival, whereas a ten degree decrease may not. In other words, accepting that the representative reaches for geomorphology, hydrology, water chemistry and temperature may not coincide, it is still going to be difficult to delineate them independently, because we do not know what the biota is reacting to.

- Each and every species may well be reacting differently to large and small changes in any one variable, and so even if we knew what every species was reacting to (which we never will), there seems to be no structured way of delineating macrohabitat zones that work for all the macrohabitat variables and all the species. Indeed the continuing discussions about what is responsible for the longitudinal biological zonation of rivers demonstrate the fact that, at any point along a river, the reactions of the biota as a whole are a reflection of the environmental influences as a whole.

- As clearcut macrohabitat zones (ie. ***composite*** representative reaches -CRRs) cannot be delineated, consequent actions seem to become impossible. We cannot now "fit" species into a recognised CRR. To explain, if we knew that a fish species had been found in water temperatures of 10, 12 and 15^{0}C, it would be nice to "fit it" into a CRR(s) with those water temperatures, and know that we had now probably defined the limits of its total distribution (total habitat) in the river. As such CRRs do not exist, we are left with the task of having to define its total potential distribution in some other way. An obvious way of doing that is to determine its range of tolerance to all the influencing variables. This is a procedure which would either involve painstaking experimental studies of its reaction to changes in each and every variable and combinations of variables, or equally painstaking collection of data on all the conditions in which it has ever been found. This would have to be repeated for every other species and then, because the species also affect each others' distributions, for all the species in combination.

We were forced to the conclusion that the macrohabitat concept was designed for single-species studies of species of special importance (eg. trout), where there is likely to be a large body of data to aid the process of macrohabitat assessment. The fact that the IFIM team does the macrohabitat assessment 'informally' (Bovee, US Fish & Wildlife Service, pers. comm.), and that we have never seen it formally reported upon in the scientific literature, supports our conclusion that it is not generally workable at the ecosystem level. The implications of this are that no matter how sophisticated the predictions of future abiotic change are, it will be impossible, using the macrohabitat concept as it stands, to predict the changes in distribution of riverine communities: **it provides a method that can only be used for very limited predictions of the change in distribution of a single species as a reaction to abiotic change**.

3. PHABSIM II has its roots as an hydraulic model, but is pushed further than is possibly valid, by being used to link its hydraulic simulations with ecological data. The link itself is less of a problem than how people interpret that link. If you accept PHABSIM II's credentials as an hydraulic model (as far as I know, assessments of this are not abundant or exhaustive), it seems valid to use it to predict how physical conditions in a river change, in terms of water depth, current speed and channel index (cover; substrate). If you accept that these same three variables are the most important ones defining the physical habitat of a species (I have never seen a clear argument by the IFIM team as to why these variables were chosen and suppose that it could be because they are the three variables that are most relevant for hydraulic models - but not necessarily for the biota), then it would be valid to use PHABSIM II to define the gain and loss of this physical habitat with changes in discharge.

Two further steps are often taken, however, which do not seem to be valid. They are explicitly NOT formally stated as part of the recommended use of PHABSIM II, but are often informally implied or applied by many users of IFIM. Firstly, the description of loss and gain of physical habitat is not a description of predicted distribution patterns of the species at the microhabitat level: it is a description of hydraulic conditions only, **and not of how the species will use those conditions**. Even more strongly, the predictions of loss and gain of physical habitat are not a prediction of the productivity of that species: one cannot equate more physical habitat with an increase in population numbers! These kinds of links would require sophisticated ecological models which would range into such areas as predator/prey relationships, nutrient cycles, community structure and function and so on.

The authors of IFIM say such extrapolations are possible, with caution, for the rivers and species for which the methodology was designed, and should be used with extreme caution outside those limits. I feel that in the USA they have a good enough understanding of, say, trout behaviour and flow requirements, to be able to make such cautious extrapolations, but in any other situation, such as here in South Africa, this is not acceptable. Bob Milhous has suggested that in this country we should use PHABSIM II for no more than examining **trends** in species-physical habitat relationships.

4. The output of PHABSIM II seems wrong to us: we feel that it should be in units of "worth" rather than in units of area. We have dealt with that in section 9.5.2. of our report, and I will not repeat it here. Suffice to say that production of the PHABSIM II results in units of area introduces uncertainty as to what exactly the output represents.

5. Many of the strange features of IFIM become clear when one considers its beginning as a tool used by the U.S. Fish and Wildlife Service to manage river flow in response to pressure from the game fish lobbies. It is designed to inform managers regarding single species or groups of similar species, and was never designed to guide the maintenance of complete river ecosystems. Even for single species, it is very restricted in its approach, as it does not cater for anything outside the immediate hydraulic conditions used by a species. Features such as links with food organisms and with habitat maintenance through flushing flows are either poorly developed or missing, so the long-term maintenance of a species could not be ensured through applying the results of the PHABSIM II simulations.

6. There are a large number of options within PHABSIM II which, while giving a good hydraulic modeller a chance to produce the best hydraulic description of a site, allow the poor modeller to fudge results. No-one seems to state which options they used, and we do not know how much difference such choices can make to the results.

7. The methodology has no clear links with the hydrological regime of the river in question, except to guide the choice of QARD values. This is one of the main inputs in South African instream flow assessments, and we were surprised at this omission.

POSITIVE ASPECTS

1. The approach is visionary in its scope, and contains a wealth of knowledge, expertise and good common sense about river research. By the time you understand it, you have been provided with an indepth (if somewhat harrowing) training in the work required for instream flow assessments. We are very grateful for the understanding and skills that we now have, and feel competent to talk about, and advise on, the ecological aspects of river flow. Not least of the benefits is our multidisciplinary training, which allows us to converse at the technical level with engineers, hydraulic modellers, surveyors, hydrologists, fluvial geomorphologists and water managers.

2. The character of PHABSIM II reflects the problems of producing accurate hydraulic simulations of low flow conditions. It offers several modelling options, including what seems to us to be its best one, IFG4, which simulates conditions at each transect in isolation through information on its stage-discharge relationship. This avoids the problem of having to have a transect at every hydraulic control, for this becomes very problematic at low flows when more and more hydraulic controls appear.

3. The cell-by-cell simulations of hydraulic conditions are geared to the ecological reality that average current speed at any point is fairly meaningless. It is an attractive feature, and we would have liked to have more time to investigate its potential.

CONCLUSION

It soon became apparent that IFIM was not suitable for the kinds of instream flow assessments presently required in South Africa. It appears to have been developed to cater for specific species of commercial or other importance, and cannot be used for assessing water requirements at the ecosystem level. It also requires large amounts of data and time, both likely to be in short supply as the rate of development of water resources in South Africa increases. It is invaluable as a training tool, but locally a more rapid, practical approach was deemed necessary and this is now being developed.

3.2 WHERE ARE WE" - An overview of the state of research on South African rivers

Jay O'Keeffe, Institute for Water Research, Rhodes University

INTRODUCTION

As a framework for this overview, I decided to revisit a figure developed by Jackie King in 1988 (Figure 2 in Ferrar *et al*, 1988) which defined the main components of river ecosystem research. This figure, reproduced in Figure 3.2.1 provides a checklist against which we can examine:

- how much we know about each of the components
- how helpful and appropriate hydraulic modelling and the biotope scale are to achieving an understanding of riverine ecology
- which components we should be concentrating on in order to improve our understanding of the effects of changing flow conditions.

THE MAJOR COMPONENTS

Water Quality

Our knowledge of the effects of changing water quality, and the different water quality components, has increased considerably over the past seven years, but is still inadequate in many aspects, particularly in predicting the consequences of changing flow regimes, and the synergistic effects of changes in the different water quality components.

The work of Dallas and Day (1993) has done much to synthesize our understanding of the different water quality in different parts of the country, and the ecological effects of individual components. There is now considerable water quality modelling expertise (eg WATERTEK and Ninham Shand) concentrating mainly on water quality in reservoirs, and the MINTEQ chemical speciation model which provides insights into the bio-availability of ions in the water. Some ecotoxicological expertise is beginning to be built up, particularly in terms of invertebrate tolerances to salinity.

The biotope scale is generally inappropriate to water quality problems which usually affect reaches of several kilometres. An exception to this would be the localised effects in pools when rivers cease to flow. Hydraulic conditions are of considerable importance in the recovery of rivers from pollution -the riffle-pool sequence providing alternate sites for precipitation/mineral cycling and re-aeration of the water. At present, very little is known about these processes in South African rivers.

Water Quantity

Research into instream flow requirements and the effects of reduced flows has been a major focus of research for the past seven years, and is the main focus of this workshop. Since it is to be covered in detail by Jackie King, there is little need to duplicate the effort here, but it is perhaps useful to examine the figure to see where there are still gaps in our knowledge.

The hydrological, hydraulic and geomorphological aspects of Instream Flow Requirements are becoming better understood than the biological consequences: hence the concentration on habitat maintenance rather than trying to manage the species themselves. Following the work of King and Tharme (1994), that of Des Weeks *et al*. (IWR) (in prep) on the Sabie River, and that of the Centre for Water in the Environment (CWE) at the University of the Witswatersrand, we now have a growing database on the hydraulic requirements of some of the life-stages of some fish species and invertebrate groups, and of the water requirements of some riparian plants. We have very little idea of the resilience of any of the biota to flow

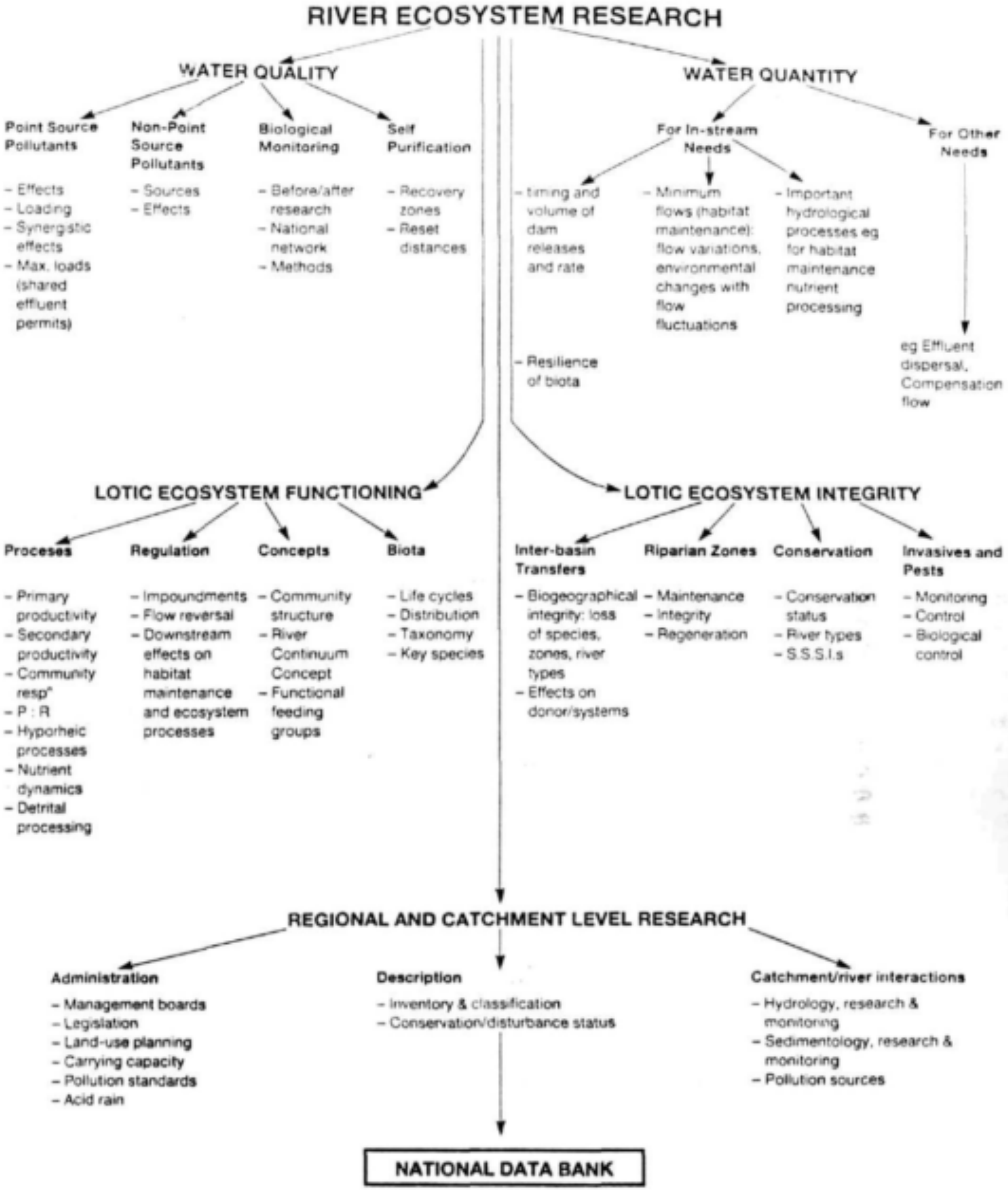

Figure 3.2.1 A framework for considering research priorities within the River Research programme (after Ferrar *et al.* 1988)

reductions, except to say that the riparian trees on the Luvuvhu floodplain proved astonishingly vulnerable to the 1992/3 drought, during which up to 80% of some riparian tree species died.

Perhaps the greatest requirement for further information is on the responses of river channels to flow changes, and the time-scales over which these operate, since these and the hydrological processes will determine the ultimate availability of habitats, and therefore the survival of the riverine biota. These important processes are being addressed by Kate Rowntree and Roy Wadeson at Rhodes University and by Andre van Niekerk and George Heritage at Wits.

Lotic Ecosystem Functioning

An understanding of the basic organic and biological processes (as listed in the figure) is still largely lacking for South African rivers. This is a consequence of the largely applied research focus in rivers. As the great majority of work is being carried out in research institutes which rely on contract funding, it has been driven by the immediate requirements of the funding agencies for answers to pressing problems of water supply and quality. The fundamental work that has been done, in the main by members of the Freshwater Research Unit at UCT, has concentrated on detrital processing and the effects of catchment fires. Community structure and functional feeding groups of invertebrates have been addressed by Carolyn Palmer at the IWR, Rhodes University and Jackie King, but the general applicability of their results outside the Buffalo River and the rivers of the western Cape is unknown.

An empirical understanding of the effects of impoundments on water quality and the biota downstream has been gained through studies on the Buffalo and Palmiet Rivers, and is being applied to the Sabie River, but many assumptions have to be made about the similarities and differences of these systems.

Under the sub-heading of the biota, there is now a reasonable database on the distribution of species in representative rivers in different regions, with glaring gaps such as the northern parts of the eastern Cape (the former Transkei and Ciskei). The taxonomy of the invertebrates is still rudimentary for many groups, and the knowledge of life-cycles for fish and invertebrates is inadequate.

Information gaps under this heading are greater than for other aspects of river ecology, and the question is how important is this lack? We have been relatively successful in answering applied questions to date, but our confidence in our answers, our predictive ability, and our ability to extrapolate from one river to another, are all crucially dependent on a more fundamental understanding of the underlying biological and ecological processes. At the moment we are using knowledge capital which was largely gained in previous decades, or has been borrowed from other countries, and we are not adding significantly to that capital.

Lotic Ecosystem Integrity

This heading refers to our understanding of the ways in which the components and processes in rivers have been interfered with, and our ability to measure these interferences.

Inter-basin transfers have become the management option for increasing the water supply in areas of low supply and high demand. Bryan Davies (FRU,UCT) and others have provided comprehensive overviews of the extent of IBTs in South Africa, and the meagre research that has so far been undertaken on them. To date, only the Orange/Fish transfer has been investigated in any detail. Studies revealed that, firstly, 5 species of fish have been transferred from the Gariep Dam to the Fish River and that, secondly, serious outbreaks of pest blackfly have resulted from the change from a temporary to a permanent flow regime. A major project on the ecological effects of IBTs is due to start under the leadership of Bryan Davies.

Research on riparian zones is at present confined to the combined efforts of Forestek and the CWE, with projects aiming to understand the water balance in the riparian strip of the Sabie River. Important questions about the role of the riparian vegetation in stabilising the river banks, and filtering nutrients from catchment runoff, remain little researched. The potential geomorphological effects of riparian vegetation have been reviewed by Kate Rowntree (Rowntree 1991).

Conservation status, its definition and measurement, have been priorities for a decade, mainly because of the need to classify rivers according to their level of degradation, and to define a 'desired state' for the assessment of Instream Flow Requirements. The term 'conservation status' has now been largely superseded by 'Index of Biotic Integrity', and methods of assessing this are currently being developed. Separately, the concept of conservation importance - the relative priority of the river for conservation, is also being addressed, but at present there is no accepted method for its measurement.

A summary of the status of invasive species has recently been produced by de Moor and Bruton (1988), so that the number and distribution of invasives is adequately known. Their effects on the indigenous fauna and the ecological processes in rivers is less well known - even the impact of introduced trout (which have been in South Africa's rivers since the late 1800s) is still a matter of dispute. Pest species, because of their economic importance, have been a focus of research, and the blackfly *Simulium chutteri* has been a particular favourite. The works of de Moor (1982) and Palmer (currently) have done much to explain the circumstances required for pest populations to emerge and the best methods of dealing with them. The regulation of flow regimes to provide constant flowing water has been largely responsible for the development of *S. chutteri* as a pest, but there has been considerable resistance to the idea of returning flow regimes to their natural cycles as a means of control. The use of selective pesticides, such as *Bacillus thuringiensis*, has been the favoured method.

Appropriate scales for researching and managing ecosystem integrity vary. The catchment scale is the most obvious scale for biogeography, IBTs and pests and invasives, while river zones might be most appropriate for riparian research and the assessment of conservation status. Changing flow regimes and deteriorating water quality are the most widespread causes of the breakdown of ecosystem integrity. The consequences of this breakdown need to be expressed in terms of the loss of usefulness of the resource if they are to be accepted as priorities for future research.

Regional and Catchment Level

The administration and legislation of water resources has largely been beyond the direct control of ecological researchers, but we have made some important inputs to the process. The recognition of the environment of rivers as a legitimate user of water (DWAF, 1986) has been a major paradigm shift, and the recent acceptance in the white paper on Water Supply and Sanitation Policy (DWAF, 1995) that: "The environment should not therefore be regarded as a 'user' of water in competition with other users, but as the base from which the resource is derived and without which no development is sustainable", is a turning point in the philosophy of water resource development. Pollution standards are gradually being defined for all the major water quality constituents, in relation to all the major users, both for the region and for individual catchments. The definition of environmental standards lags behind, but is being addressed.

Several major initiatives have been undertaken to inventorise and classify rivers in the past few years. Hydrological, water quality, geomorphological, and ecological classifications are being completed, and there is some effort to ensure that the results are compatible. The scales at which these classifications are being effected has been regional or sub-regional, largely in order to provide some idea of how far information on one river can legitimately be extrapolated to another, but it seems that there may be more commonality between similar zones of different rivers than between the different parts of the same river.

Catchment interactions with rivers continue to be a neglected connection, except in terms of hydrological modelling. A study being completed on the effects of land-use changes on the rivers of the Wilderness Lakes seems to show that there has been very little change in either since the 1960s, but the deterioration in the flows in the rivers of the Kruger National Park indicate that catchment changes have had a major impact in the northern and eastern Transvaal. Recent research on the Bell River in the Eastern Cape Drakensberg has indicated that increased catchment erosion may have been a contributing factor causing channel instability (Dollar and Rowntree 1995). The hierarchical geomorphological model of Wadeson and Rowntree (1994) aims to provide a framework through which these catchment-channel interactions can be addressed.

What's Missing?

The attached 1988 listing of research priorities proves to be an enduring definition of the kinds of information that we need in order to understand the ecology of rivers and to provide useful advice to water resource managers to help them to plan the sustainable use of South African rivers. The main change in direction since 1988 has been the recognition of the necessity to link environmental research to the needs and desires of the people living in the catchments. The change of government and the objectives of the government's Reconstruction and Development Programme (RDP) require that water resources be developed to meet the basic requirements of people for a minimum supply of clean water (25l per person per day) within 200m of their dwelling. At present, some 17,500,000 people are without access to piped water supplies, and in the short-term provision to them is to override all other considerations. If ecological research is to continue to be seen as relevant, it must therefore be firmly linked to the sustainable supply of water to the majority of people.

One area that is of the utmost priority therefore is to develop ways of ascertaining the requirements of people in a catchment, and of defining the `desired state' of the river in their terms. At present, this `desired state' is normally defined by a sociologist, often not resident in the catchment, and without the resources to undertake a survey of the desires of residents.

CONCLUSIONS

- Although our knowledge of the ecology of rivers has increased greatly since 1988, the main advances have been in the application of empirical information to immediate problems, and our ability to understand processes and predict with confidence is still rudimentary.

- The biotope scale may be appropriate and necessary to the understanding of questions associated with flow requirements and some of the geomorphological changes consequent on flow reductions, but larger perspectives are generally required to solve problems associated with water quality, ecosystem integrity and (obviously) regions and catchments.

- Hydraulic modelling is probably the best route to achieving an understanding of the changes in habitat availability, and therefore changes in species abundance and distribution, in response to flow modification. In itself, achieving this level of understanding is a formidable task, but we should not forget that there are a whole suite of complicating factors, most of which are listed in the attached figure, which operate at other scales.

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3.3 THE BIOTOPE CONCEPT: A GEOMORPHOLOGICAL PERSPECTIVE

Roy Wadeson, Geography Department, Rhodes University

INTRODUCTION.

The link between ecology and fluvial geomorphology is well recognised, but is generally poorly understood, largely due to the complex relationships that exist within catchment processes. Ecologists recognise that a variety of factors control the abundance, distribution and productivity of stream dwelling organisms, such as competition for space, predation, chemical water quality, nutrient supplies, the presence of waterfalls or dams, and flow variability (Gordon *et al.* 1992). Furthermore, there is a fundamental understanding that these control factors are largely a response to those physical processes which form the "structure" within which an organism makes its home. Because physical factors are generally more predictable, less variable and more easily measured than biological or chemical ones, it is reasonable to put the emphasis on a group of physical parameters which can be universally and easily determined, with the knowledge that widely separated streams and rivers having very similar abiotic features may have parallel and ecologically similar faunas (Pennak 1971).

At the lowest level within the classification hierarchy being developed by Wadeson & Rowntree (1994), an attempt is made to examine the relationships between ecologically significant environments (biotopes) and flow characteristics such as flow depth, mean and near bed velocities, and substrate size. Such a system may aid the prediction of channel adjustment and associated biotope transformation in response to changes in the flow and sediment regime.

THE BIOTOPE CONCEPT - What is it?

The biotope may be defined as a spatially distinct in-stream flow environment characterised by specific hydraulic attributes. A single morphological unit may be composed of a number of biotopes. The use of the term biotope follows that of Whittaker *et al* (1978), Price (1975) and Ward (1992) who all make a clear distinction between the term `habitat', the abiotic environment of a species, and the term `biotope', the abiotic environment of a community. This is a scale based distinction well recognised by many South African authors (Harrison & Elsworth 1959, Chutter 1970, de Moor 1990).

Table 3.3.1 gives examples of some of the biotopes recognised by lotic ecologists together with an objective definition for their recognition based on the findings of Jowett (1993).

Central to the theme of this paper is an understanding that different biotopes occur as a result of geomorphological processes of erosion and deposition which determine their physical structure. In the geomorphological literature these structures are referred to as morphological units, the usage adopted in this paper. A single morphological unit may encompass a range of flow environments and substrate conditions and is of a scale better related to the community rather than the individual species. It follows that it is more logical to equate them to the community based biotope than the species based habitat.

Table 3.3.1 Definitions of selected biotopes (after Wadeson 1994)

Biotope	Biotope Definition	Biotope Definition using Froude Number *(Jowett 1993)*
Riffle	These are characterised by shooting flow with a steep, broken water surface. They are high points of coarse sediment deposition in an undulating bed long profile and have a low depth to substratum ratio.	Greater than 0.41
Run	These are characterised by tranquil smooth flow with velocity sufficient to cause some surface disruption. They are found within any substratum and have a high depth to substratum ratio.	Ranges from 0.18 to 0.41
Pool	These are characterised as being deep, slow flowing areas with no surface disruption. They are low points within an undulating bed long profile where fine sediment accumulates on the bed.	Less than 0.18

THE MORPHOLOGICAL UNIT AND THE ASSOCIATED BIOTOPES - What is their relationship?

Table 3.3.2 illustrates some of the morphological units recognised within the fluvial geomorphological literature, associated with these units are the biotopes intuitively recognised by lotic ecologists (Wadeson 1994)

CHANNEL HYDRAULICS - How can we characterise biotopes?

Clearly, an important link between morphological units and biotopes is the spatial and temporal variation in flow hydraulics associated with the different features. Previous attempts to define biotopes in terms of depth, velocity and substrate failed because values could not be transferred between channels of different scales. The use of functions which combine depth, velocity and substrate in a manner that is independent of scale would provide a more objective definition of biotopes and a link to the morphological units which support them.

Two dimensionless numbers that characterise mean motion or flow down a river channel due to gravity are the Reynolds number and the Froude number (Smith 1975). Although these two values are by no means adequate descriptors of the hydraulic environment experienced by aquatic organisms, they are useful indices to characterise the mean flow characteristics experienced within a column of water.

The Reynolds number, Re, is a way of describing how easily fluids flow and is given by:

$$Re = (V \times D) / v$$

Where V = mean velocity at 0.4 depth, D = depth, and v = kinematic viscosity.

The Reynolds number represents the ratio of inertial forces (the resistance of an object or fluid particle to acceleration or deceleration) to viscous forces (how rapidly a fluid can be deformed) and provides information on the laminar or turbulent nature of the flow. Flow is laminar if the Reynolds number is below 500 and turbulent if it is above 2000.

Table 3.3.2 Examples of morphological units and associated biotopes (after Wadeson 1994)

ALLUVIAL CHANNELS			***BEDROCK CHANNELS***		
Riffle *(Sand and Gravel bed channels)*	These are topographic high points in an undulating bed long profile. They are spaced 5-7 channel widths apart and are composed of coarser sediment such as pebbles (Leopold et.al. 1964). At low flow, riffles have rapid, shallow flow with a steep water surface gradient, and act as a broad - crested weir.	Allen (1951) **Riffles, Stickles**. Harrison and Elsworth (1959) **Riffles, Stickles**. Chutter (1970) **Stickle**. De Leeuw (1981) **Riffle**. Pridmore and Roper (1985) **Run**. Grossman and Freeman (1987) **Riffle**. Pridmore and Roper (1985) **Run**. Bisson *et.al.* (1988) **Riffle**. Boulton *et.al.* (1988) **Riffle**. Anderson and Morison (1989). **Riffle**. King *et.al.* (Pers.Comm. 1992) **Riffle**.	**Waterfall**.	This is a site at which water falls vertically; a cataract is a step-like succession of waterfalls (Selby 1985).	De Leeuw (1981) **Falls, Cascades**. Bisson *et.al* (1988) **Cascades**. Anderson and Morison (1989) **Cascades, Waterfalls**. King *et.al.* (pers. comm.1992) **Waterfalls, Cascades**.
Pool *(Sand and Gravel bed channels)*	These are low points with sandy beds although scour at high discharges may expose coarse lag sediment, which is then covered by sand during periods of low flow (Hack 1957, Lisle 1979). At low flow the pool is deep and slow flowing with a gentle slope.	Allen (1951) **Pools, Runs, Flats**. Harrison and Elsworth (1959) **Pools, Runs, Flats**. Chutter (1970) **Run**. De Leeuw (1981) **Pool, Glide**. Bisson *et.al.* (1988) **Pool, Backwater, Glide**. Anderson and Morison (1989). **Pool, Run, Backwater, Glide**. King *et.al.* (Pers.Comm. 1992) **Pool, Run, Backwater**	**Pool**	These form as erosional features below a resistant strata (plunge pools), they may also form behind resistant strata lying across the channel.	Allen (1951) **Pools, Runs**. Harrison and Elsworth (1959) **Pools**. Chutter (1970) **Run**. De Leeuw (1981) **Pool, Glide**. Bisson *et.al.* (1988) **Pool, Cascade, Glide**. Anderson and Morison (1989) **Pool**. King *et.al.* (Pers.Comm. 1992) **Pool, Run**.
Step-Pool *(Boulder bed channels)*	These are characterised by large clasts organized into discrete channel spanning accumulations that form a series of steps separating scour pools containing finer material (Grant *et.al.* 1990).	Allen (1951) **Cascades**. Harrison and Elsworth (1959) **Cascades**. Chutter (1970) **Cascades**. De Leeuw (1981) **Cascades, Waterfall**. Bisson *et.al.* (1988) **Cascades**. Anderson and Morison (1989) **Cascades**. King *et.al.* (Pers.Comm. 1992) **Cascades, Waterfalls**.	**Rapid**	These are part of the long profile in which the flow of water is broken by short steep slopes. Rapids may be completely drowned by the flow at high discharges when turbulence at the water surface is the only evidence of the underlying profile irregularity (Selby 1985).	Allen (1951) **Cascade**. Harrison and Elsworth (1959) **Cascade**. Chutter (1970) **Cascade**. Anderson and Morison (1989) **Rapids**. King *et.al.* (pers. comm.1992) **Chutes, Rapids**.

The Froude number, Fr, is defined as

$$Fr = V / \sqrt{gD}$$

Where V = velocity at 0.4 depth, measured upwards from the bed; g = acceleration due to gravity; D = depth.

Henderson (1966) described the Froude number as a "universal indicator of the state of affairs in free surface flow" (p39). It relates inertia forces to gravity forces and is important wherever gravity dominates as in open channel flow. It is used to differentiate tranquil or sub critical flow ($Fr<1$) from rapid or super critical flow ($Fr>1$) (Chow 1959).

For the sake of completeness, a detailed ecological survey should include values that describe the micro flow environment near the stream bed such as the roughness Reynolds Number, shear stress and the thickness of the laminar sub-layer.

EXPLORATORY DATA ANALYSIS - an initial attempt to assess the usefulness of simple hydraulic indices to characterise biotopes.

Exploratory data analysis has been carried out for a number of study sites within South African Rivers. Box plots were used to show whether any patterns of distribution exist for the Froude and Reynolds numbers, both temporally (at different discharges), and spatially (across biotopes). This analytical technique is particularly useful for studying symmetry, checking distributional assumptions, and detecting outliers.

The use of discriminant analysis on data from the Great Fish river suggest that both the Froude number and Reynolds number together may be useful hydraulic indices to characterise biotopes. As indices on their own, the Reynolds number does not appear to be as useful as the Froude number on its own.

Figures 3.3.1 to 3.3.3 represent the results of findings from the Sabie river (E. Transvaal), the Great Fish river (E. Cape) and The Olifants river (W. Cape). All of these systems represent widely varying fluvial and sedimentological environments. Of interest from these results is the fact that the Froude number appears to be equally useful in all rivers for the characterisation of biotopes.

Results from the Sabie river indicate that despite the large spatial variability of like biotopes, Froude number variability within biotopes is surprisingly consistent. Results from the Olifants and Great Fish river indicate the usefulness of Froude Numbers to characterise temporal changes in biotopes as a result of changing discharge.

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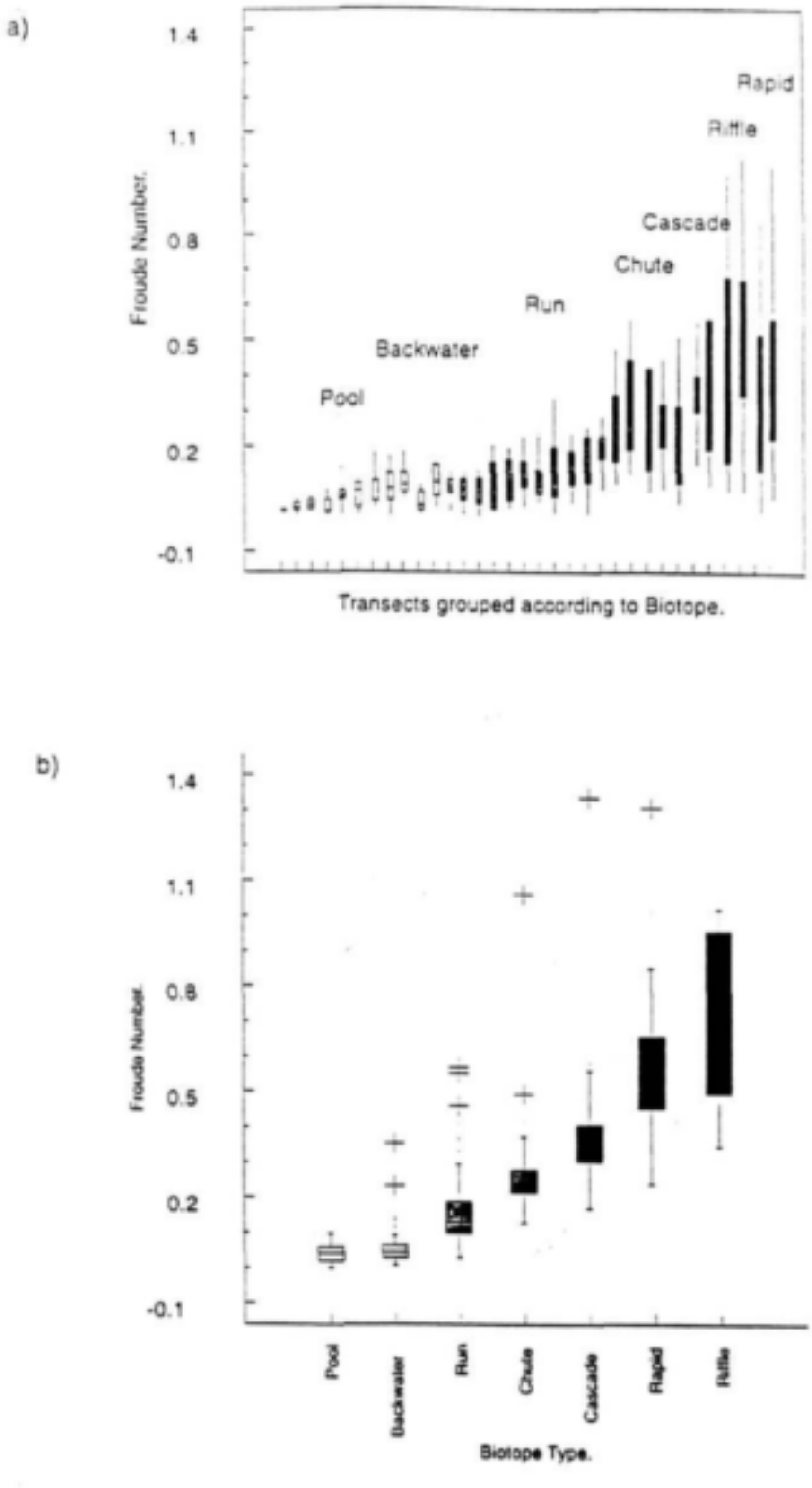


Figure 3.3.1 Biotopes in the Sabie River characterised by Froude number: a) multiple box and whisker plots showing variability of Froude numbers from 6 different reaches within two separate segments; b) aggregated Froude numbers for biotopes. Box represents median and inter-quartile range.

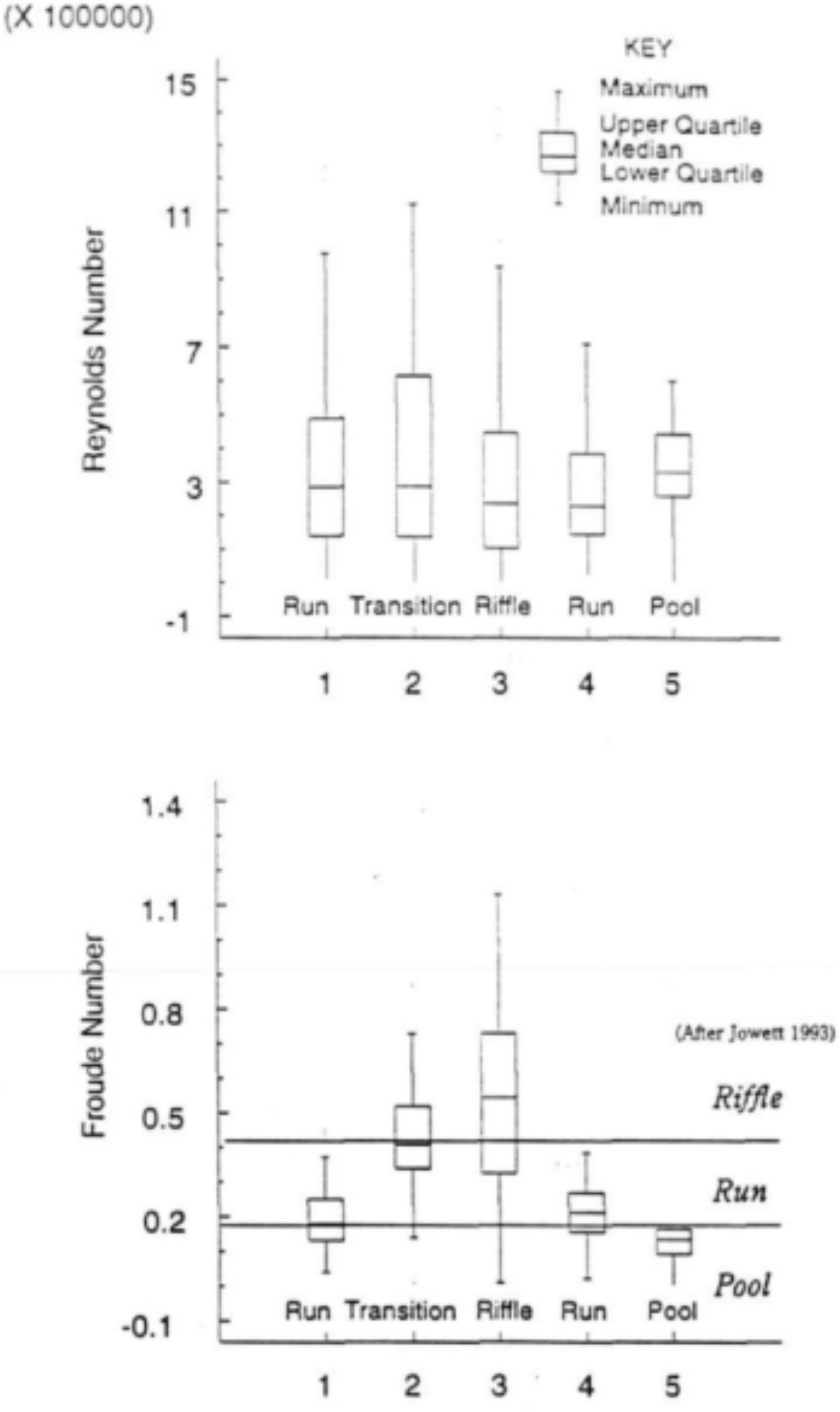


Figure 3.3.2 Variation of Froude and Reynolds Numbers with discharge for biotopes in the Great Fish River

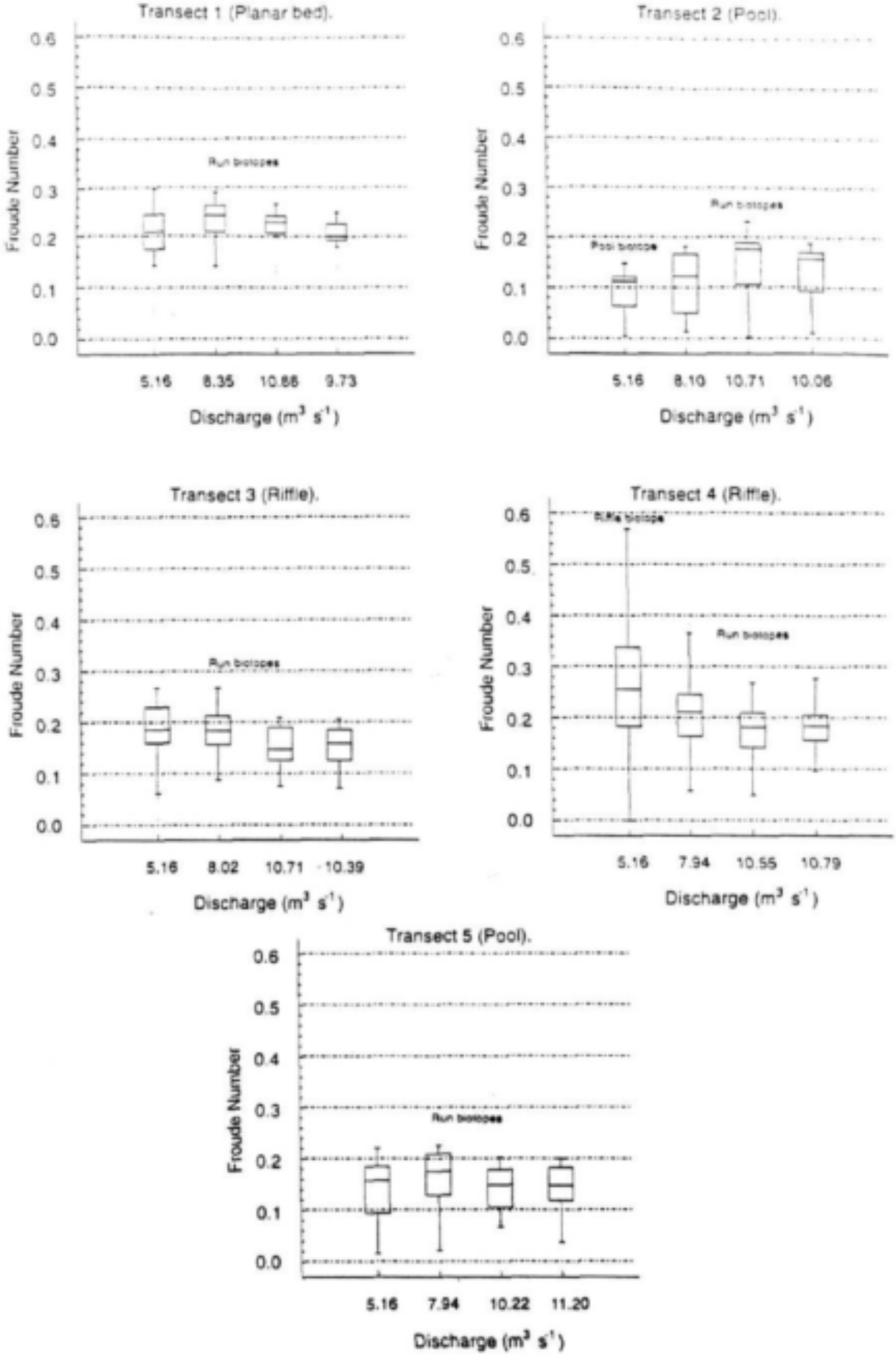


Figure 3.3.3 Variation of Froude number with discharge for biotopes in the Olifants River (Western Cape)

3.4 APPLICATION OF HYDRAULIC MODELS

Bill Rowlston, Department of Water Affairs and Forestry, Pretoria

This paper presents a brief history of my involvement in using open channel hydraulic modelling techniques to provide data of use to aquatic scientists and other biologists, specifically in the assessment of the ecological flow requirements of South African rivers.

January 1991: Nyl River Floodplain

Here I used a 2-dimensional unsteady flow model (BOSS DAMBREAK) to model the progression of flood waves along the broad, shallow floodplain of the Nyl River in the Northern Transvaal. The aim was to contribute to the determination of an ecologically acceptable flow regime in the floodplain, in the context of a proposed storage dam in one of the tributaries. Output from the modelling exercise was used to derive levels and durations of flooding resulting from a series of inflow hydrographs. Biological information comprised elevations and inundation requirements of various zones of vegetation: aquatic; low elevation floodplain; high elevation floodplain; and terrestrial. Comparison of the two sets of information, together with observations about the historical flooding regime in the floodplain, enabled some statements to be made about the flow requirements of the system.

The hydraulic modelling was quite coarse, in many ways rather unsatisfactory, and never brought to a proper conclusion. This was, however, the first time in my experience that formalised hydraulic modelling was used in conjunction with hydrological and biotic information, in an attempt to describe an ecologically acceptable flow regime.

March 1991: 1st Annual Research Meeting of the Kruger National Park Rivers Research Programme.

Whilst water resource developers and managers habitually described water requirements in terms of intangibles such as instantaneous flow rates in cubic metres per second, long-term requirements in millions of cubic metres per year, biologists used more accessible parameters such as depth of flow, current velocity, wetted perimeter, and duration of inundation. It was apparent that fairly simple hydraulic modelling could provide the link between the two ways of expressing water needs. At the Kruger National Park Rivers Research meeting I described the sort of modelling techniques available and the information required to model at scales from whole river reaches to short, essentially independent stretches. Apart from the normal output from such modelling exercises (depth, velocity, wetted perimeter, etc), I mentioned that some idea of sediment transport potential could be derived fairly readily by recourse to simple devices such as the Shields Diagram, or the Liu Diagram, both of which deal with thresholds of particle movement.

The response to my offer to undertake such modelling was completely underwhelming, and it was another year or so before researchers on the Programme realised that hydraulics and geomorphology was the link between hydrology and biology in determining the ecological flow requirements of rivers. This is probably the first time I was ever ahead of the pack: it is unlikely to happen again.

November 1991: South African Hydrological Symposium, Pietermaritzburg - *Modelling River Flow: Differences Between Engineering and Environmental Hydraulic Models* by King & Rowlston

In this paper hydraulic modelling was discussed in the general context of Jackie King's then ongoing work on the American Instream Flow Incremental Methodology (IFIM), in particular with regard to the use of the Physical Habitat Simulation Model (PHABSIM II) which is an important component of the methodology.

A number of important distinctions were made between the requirements of hydraulic modelling for purely engineering purposes, and for environmental ends. One of the most important differences (and one which in my opinion has informed environmental hydraulic modelling since) was that engineering modelling was generally carried out for high flows (*inter alia* in respect of delineation of floodlines *vis-a-vis* compensation, and structural adequacy of water works), whilst the emphasis in environmental hydraulics was on low flows (the so-called low flow requirements for ecological survival). In the former case the detail of channel shape, roughness element definition, location of hydraulic controls, etc, can be relatively coarse, and the results of the modelling are much less sensitive to inaccuracies in input parameters. In most cases some level of calibration data is available, as floods are regularly studied by the department. Effective environmental modelling, on the other hand, requires much more precise definition of the channel boundaries, including knowledge about the size of roughness elements, and good estimates of the location of hydraulic controls. Whilst most engineering applications need velocities to be calculated only as an average across the channel, linking hydraulic conditions with the preferences of biota requires knowledge of how the velocity varies in the cross-section - the cell velocities of PHABSIM II -which are discussed later.

It is appropriate here to make some comment on the hydraulics component of PHABSIM II, which I used quite extensively on Jackie King's behalf to model (part of) the Grootfontein site on the Western Cape Olifants River, as part of her Water Research Commission project. The programme has many faults, the most serious of which (in my opinion) is that poor descriptions of the purposes and uses of the many input parameters make it very easy to unwittingly obtain spurious results. (More sinister is that an unprincipled modeller can deliberately manipulate the routines to obtain the results he or she wants, with little probability of the deception being discovered by anyone other than an equally experienced modeller). But the model does have some very important advantages over more traditional techniques. One is that of flexibility: cross-sections can be modelled either completely independently (which then relies on the skills of the modeller to define the extent of interpolation between individual cross-sections), or sections can be linked together and modelled as an hydraulic continuum. (Interestingly, the New Zealand version of PHABSIM II, called RHYHABSIM for River Hydraulics and Habitat Simulation, does not have this flexibility built in, but relies entirely on hydraulic simulation using the standard step backwater calculation method. RHYHABSIM is much easier to use, but an implicit requirement is that channel cross-sections define the reach completely at all flow rates, not easy for very low discharges). Secondly, PHABSIM II provides an opportunity to calculate average velocities in the water column in individual cells across each cross-section. This is not without its problems, and requires care in collecting calibration data for cell velocities: the location of the point of average velocity is difficult to define where the size of roughness elements approaches the depth of flow. This was illustrated in the riffles at Grootfontein, where the observed velocity profiles in some cells did not show a monotonic increase with increasing discharge, and the model, which expects such an trend, gave extrapolated results for higher discharges which were difficult to interpret. These problems apart, the cell velocity provision seems to me to be useful in defining changes in the mosaic of useful habitat as discharge changes. (That is to say, probably for fish more than for benthic dwellers, as it occurs to me that average column velocity almost certainly does not accurately reflect the actual velocity fields experienced by animals which live on or under rocks on the stream bed. This is also not a very original thought).

One additional advantage of IFIM in the United States of America is that it has institutional acceptability: the flow regime recommendations from IFIM studies are more readily accepted by decision makers because of the body of knowledge and expertise behind the methodology, and its reputation. The developing Building Block Methodology (BBM) is beginning to acquire similar status in South Africa.

Building Block Methodology (BBM)

Hydraulic modelling in the Building Block Methodology comprises developing, for relatively short lengths of river channel (a riffle, for instance), relationships among discharge and depth, velocity, wetted perimeter, etc. This can be achieved without excessive difficulty using simple 1-dimensional steady state models. Care is however required in the selection of channel cross-sections in the analysis, in that riffles can be drowned out by the downstream pool as discharge increases, and in some cases the prevailing flow regime in the riffle can change from supercritical to subcritical as discharge changes, with concomitant changes in depth, velocity, etc. Most of the simpler models use Manning's 'n' as a measure of roughness element size, and it must be borne in mind that this parameter is dependent on the ratio of water depth to size of substrate element, and is therefore not constant for all discharges. Where the size of the substrate becomes a significant proportion of the total depth, estimation of Manning's 'n' become difficult, and calibration data in the form of observed water levels at known discharges becomes essential. It is unfortunate that the parts of rivers which are easiest to model using standard open channel techniques - channels with simple cross-sectional shapes, with uniformly sized roughness elements which are small in comparison to flow depth - are of much less interest to aquatic scientists than the hydraulically complex riffles at low flows, which are much more difficult to model.

The simple models also assume that the bed of the channel is immobile, not an unreasonable assumption at low discharges. They can give only coarse estimates of whether sediment derived from upstream will pass through the section or be deposited on the bed. The full integration of hydraulics and fluvial geomorphology requires relatively sophisticated modelling techniques, and still has some way to go before predictions of the effects of changing flow regimes can be made with confidence.

3.5 APPLICATION OF A HIERARCHICAL GEOMORPHOLOGICAL MODEL TO SELECTING REPRESENTATIVE REACHES

Kate Rowntree, Department of Geography, Rhodes University

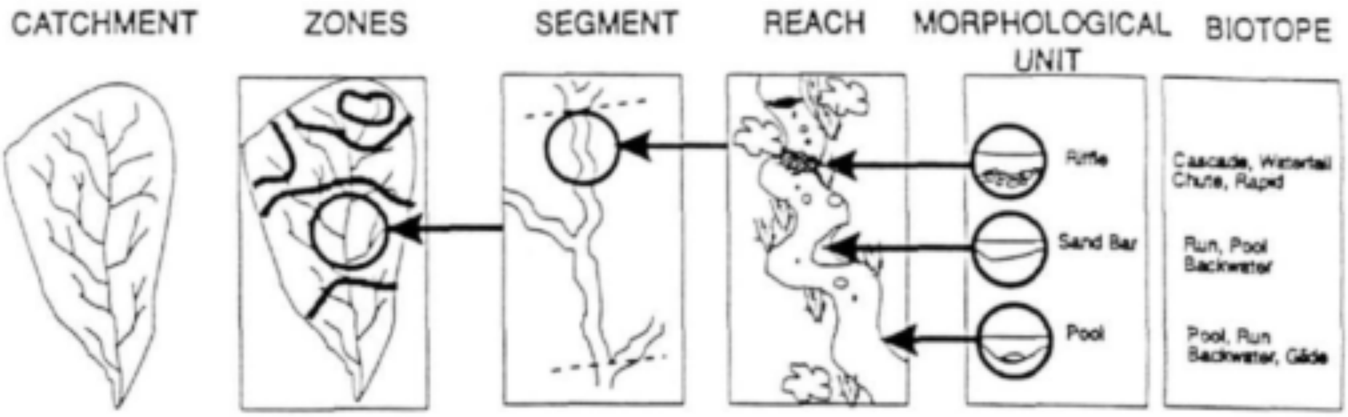
This workshop was the culmination of a visit to South Africa by Malcolm Newson. Over the last two weeks I have had the opportunity to accompany Malcolm to a number of rivers in different parts of the country, to compare the physical characteristics of river systems in South Africa and the U.K. and to discuss alternative approaches to applying a geomorphological perspective to the management of rivers. I would like to take the opportunity to address two of the issues which have arisen in discussions. The first is the uniqueness of river systems and the problem of extrapolation both within and between systems. The second is the need to place the assessment of habitats within the context of river networks. The application of a hierarchical methodology is proposed as a means of addressing both these concerns.

We can start by asking the related questions 'Can we compare either within or between river systems and at what scale is it possible to classify river features?' River catchments occupy a unique geographic position and therefore must have a unique assemblage of attributes associated with them. This makes classification at the catchment scale problematical. At this scale it is useful to distinguish between three groups of attributes: those related to the regional morphology or the SKELETON, those relating to the sediment availability or the FLESH, and those relating to the transport power or the BLOOD STREAM. These can be summarised as follows.

	Attributes	Factors
The skeleton	long profile, network shape, valley form	geological history - tectonics, sea-level change, climatic change, erosion cycles
The flesh	soil depth, soil erodibility, particle size	geology (rock type), weathering and erosion cycles
The blood stream	flow regime	climate - regional water balance, seasonality, interannual variability, cyclicity

Within South Africa there is considerable variability in all the above factors. The history of climatic change, although applicable to broad regions, shows important differences between for example the south west and the north east. Tectonic activity has had a differing impact in different areas; Pliocene uplift for example was concentrated along an axis from Natal through the Eastern Cape, with greatest uplift in Natal. Regional geology clearly changes across the country, along with the rainfall-evaporation balance. The regional distribution of these separate factors intersect to give a complex grouping.

If we compare South Africa with Britain we come across further differences. Whereas tectonic instability and relative climatic stability have dominated South African landscapes over the last 2.5 mill. years, Britain has been characterised by greater tectonic stability but a major hiatus in the climate in terms of a series of glacial epochs. Whereas Africa in general is characterised by long periods of chemical weathering and accumulation of deep soil profiles, the glacial period in Britain



THE MODEL HIERARCHY	DEFINITION OF TERMS USED.
CATCHMENT	The land surface which contributes water and sediment to the specified stream network.
RESPONSE ZONE	Areas within the catchments which can be considered as homogeneous with respect to flood runoff and sediment production.
SEGMENT	A length of channel along which there is no significant change in the imposed flow discharge or sediment load.
REACH	A length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occur.
MORPHOLOGICAL UNIT	The basic structures comprising the channel morphology for example pools, riffles, runs, rapids, waterfalls etc.
BIOTOPE	The habitat assemblages with a characteristic range of temporarily variable hydraulic and substrate characteristics which can be associated with the morphological units.

Figure 3.5.1 A hierarchical geomorphological model for describing river systems

was responsible for severe scouring of soil materials from upland areas and deposition of glacial deposits in valley bottoms and lowlands. Much of the material available to British rivers is therefore of glacial origin and tends to be well sorted. The climate of Britain is also very different from South Africa, with higher runoff coefficients resulting from much lower evaporation rates, a less marked seasonality and a lower interannual variability. Given these basic differences it is unlikely that river systems in South Africa and Britain will be directly comparable.

Not only do regional differences exist as described above, but within catchments there are distinct changes. These relate firstly to continuous downstream changes due to increments (or abstractions) of water and sediment, a function largely of the climatic gradient between the upland and lowland areas. Local variability exists due to geology, riparian vegetation and the imprints of tectonic activity or sea-level change which have impacted on valley floor gradient or valley form.
Given the great variability in channel controls, both within and between catchments, how and at what scale can comparisons be made? Direct comparisons are probably only possible at the smallest scale: grains (sand grains and cobbles) or bedforms (ripples and dunes) can be equated world wide. Common morphological units such as rapids, riffles or pools can be recognised and compared over wide areas, but already at this level distinct regional differences may occur. Field discussions with Malcolm Newson indicated for example that the perception of a riffle differed between South African and British researchers: although both could be equated in terms of formative process, the British riffle tended to have a much smaller particle size and less broken water than the South African equivalent.

As the size of the unit increases, then so does the uniqueness of the feature and it becomes more difficult to make comparisons or to derive meaningful classifications. Our own work has moved away from attempts to classify above the scale of the morphological unit, but rather to develop a methodology for describing whole river systems in terms of their component parts (Wadeson and Rowntree 1994). The hierarchical model summarised in Figure 3.5.1 allows a larger system to be broken down into successively smaller units, which facilitates sampling. It also allows smaller units to be related back to the larger framework, aiding extrapolation and an assessment of potential change.

The hierarchical framework provides a logical means of selecting representative reaches in a river for which there is limited information on channel characteristics. The first step is to identify sediment source areas and runoff zones so that the main channel, or tributary of interest, can be broken down in to segments, classified according to an index of the ratio between transport capacity and available sediment. Segments are further subdivided into reaches which differ in terms of local controls and therefore in terms of channel processes and the resultant channel forms. Gradient is used as a primary determinant of reaches.

Once reaches have been identified from topographic maps, aerial photographs and, increasingly in IFR assessments, an aerial video, it is possible to select appropriate reaches for site visits. Morphological units and associated biotopes are identified at this stage. Once the distribution of reaches is determined and they have been described or classified in terms of their morphological units, representative and/or critical reaches can be selected for biological and hydraulic studies.

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3.6 THE USE OF HYDRAULIC MODELLING OF PHYSICAL BIOTOPES IN SOUTH AFRICAN INSTREAM FLOW ASSESSMENTS

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1. The South African Department of Water Affairs and Forestry (DWAF) has recently changed its policy from one of water supply, more or less on demand, to one of holistic management of water resources. This has resulted in the recognition that some part of the total runoff of each river must be reserved for maintenance of the riverine ecosystem. Following this has come the requirement from DWAF that river scientists provide an answer regarding the amount of flow that should be reserved for maintenance of any particular river targeted for water-resource development. This answer is provided through some kind of instream flow assessment.

2. In the short to medium term, instream flow assessments in South Africa will largely consist of "quick response" actions, because little time, data and money will be available to provide answers. After finding the available international approaches incomplete, too complicated or costly, or not relevant, the South African community of river experts (scientists, engineers and water managers) began collaborating on development of an approach that would cater for the realities of the current situation. The present working name for this approach is the Building Block Methodolgy (BBM) methodology.

3. The BBM methodology is based on existing, or easily collected, data and on best available knowledge and expertise. A structured sequence of events is followed (and is continually being further improved) to acquire the data and present it in the most user-friendly way to the experts. The experts meet in a workshop to consider the data and, led by experienced group leaders, to compile from scratch a recommended modified flow regime for the river of concern. This is the Instream Flow Requirement or IFR. This information is then forwarded to the water managers for negotiations and decisions. About 15 such workshops have now taken place in South Africa, and one is now required by DWAF as an early stage of any new water-resource development.

4. Hydraulic and geomorphological data are used in the BBM methodology in two ways. Firstly, the geomorphological character of the channel, among other factors, is used to choose reaches within the predetermined study area. These are the reaches within which IFR sites will be situated. All hydraulic and hydrological simulations will be focused on these chosen IFR sites. As many ecologists will not be familiar with hydrological terms such as cumecs ($m^3\ s^{-1}$) and will not be able to envisage what (say) 10 cumecs looks like, translation of these kinds of data into DEPTHS and VELOCITIES of water at the IFR sites is the vital link that enables communication with engineers. If the reaches and sites are not representative of their sections of the river, then the ecologists will be basing their judgements on information of unknown quality.

5. Once the sites are chosen, cross-sections are surveyed in to provide the information for the hydraulic model. Again, choosing the right cross-sections is vital. Between them the cross-sections should describe not only typical physical habitat, but also critical physical habitat. To explain, a river section might consist almost entirely of a sandy channel with marginal vegetation inundated on the edge: this typical habitat must be described by at least one cross-section. But there may also be one small cobble riffle, which may be the only habitat in a very long stretch of river for riffle-dwelling species or as spawning grounds for fish: this critical habitat must also be described by a cross-section.

6. Bearing the problems of representativeness in mind, riffles are often the favoured biotopes for IFR cross-sections because they are the first biotopes within the main channel to dry out on a falling discharge. The reason they are favoured is that if the flow is managed to keep riffles in good condition, much of the rest of the river ecosystem should also be catered for. They are also useful areas for hydraulic modelling

as they are hydraulic controls, so beloved by hydraulic modellers. Hydraulic controls are very important in IFR studies for the following reasons:

- the base flows or, to avoid an hydrological term with unknown implications, the low flows, will probably comprise about three-quarters of the IFR. Being potentially such a large proportion of the total IFR, it is vital to prune this low-flow requirement down as far as is acceptable, or one could end up asking for an unreasonable amount of the virgin MAR
- with the accent thus firmly on the low flows, accurate hydraulic modelling of low-flow conditions becomes vital. This is not easy, because most hydraulic models need information on each and every hydraulic control within the reach of concern and hydraulic controls increase in number with decreasing discharges until at very low flows virtually every boulder forms such a control
- it is thus useful to be able to focus in on single cross-sections which at low flows will have stage-discharge relationships not influenced by downstream conditions - i.e. RIFFLES, and to simulate hydraulic conditions for these. Pools are more complicated to obtain good hydraulic simulations for, as they are influenced by downstream hydraulic controls which must be taken into account.

7. River ecologists will use the hydraulic information on the cross-sections to judge whether or not the water at different discharges will be of acceptable depth for specific ecological purposes. From this judgement, and their considerations of the hydrological record for the river, they will compile a recommended modified flow regime. Thus the hydraulic predictions for the cross-sections become a vital communication link between the engineer and the ecologist, and to a large extent the success of the instream flow assessment depends on their accuracy.

8. The most useful cross-sectional data are:

- channel profile, in detail, or at least at every major change in slope and substrate particle size
- information on the substrates: sand, small cobble, bedrock and so on
- location and identity of any instream vegetation
- location and identity of riparian vegetation, including species zonation up the banks
- whether secondary channels fill at the same time as the main channel or remain dry until the main channel banks overtop
- the height of different discharges in the channel, ie the stage-discharge relationship
- wetted perimeter-discharge relationship
- height of floods of different return periods: 2y, 5y, 10y

9. Other useful information would be an attempt at identifying bankfull discharge, and whether or not this represents the `channel maintenance' flood. This leads on to the fact that, for IFR purposes, geomorphologists need to be able to define which components of the whole flow regime are most important for maintaining the geomorphological character of the river at some predetermined status. Ecologists are already attempting to do this for the purposes of ecosystem maintenance.

IN SUMMARY

For IFR purposes it is necessary to have accurate hydraulic predictions of the height of flow at various discharges at a selection of representative sites and cross-sections. Due to time constraints, it may not be possible to survey these cross-sections at different discharges or even when there is water in the river! Nevertheless, the hydraulic predictions that are then produced have to be sufficiently accurate to allow rivers scientists to compile a recommended modified flow regime.

Beyond this work are further interesting avenues of research for hydraulic modelling, which are not considered here. These include defining geomorphological units and their hydraulic conditions, and determining which of these units are different in ecological terms.

In conclusion, I feel that the best alternative to a PHABSIM II approach is for the modellers to model down to the level of the biotope and the ecologists to study ecosystems at the level of the biotope. Each discipline is then staying within its field of expertise, and links between the two should be through careful collaborative work at the biotope level.

3.7 INSTREAM HABITAT: GEOMORPHOLOGICAL GUIDANCE FOR HABITAT IDENTIFICATION AND CHARACTERISATION

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ABSTRACT

This paper addresses the problem of standardised identification and interpretation of instream habitats, which has been hindered in the past by reference to flow dependent, site specific criteria and ambiguous, qualitative terminology. A sample of river reaches in North-East England rivers was selected on the basis of achieving an extensive range of morphological units. Units were subjectively defined on the basis of flow type, sediment size, channel gradient and cross-sectional width-depth measurements. Standard terminology is suggested for morphological units, and the habitat hydraulics of each unit measured by data collection procedures consistent with the requirements of the instream habitat assessment model PHABSIM.

The subjective classification of morphological units used to typify sample reaches was then tested by discriminant analysis, to determine whether a priori defined units are hydraulically and morphologically discrete. Discriminant analysis allocates cells to a particular habitat type on the basis of combination hydraulic and morphological indices (Froude number, depth:width ratio, relative roughness). Provisional results are presented for all sites at two discharges: Froude number is successful in classifying pools at low flows, although relative roughness is a better index for pools at sites where large boulders or fine gravels are the dominant substrate size. The Froude number is less successful for units with turbulent, rough boundary flow. Active depth:width ratio more successfully identifies riffles and cascades, as there is less variation on the range of values of this index.

Morphological units with turbulent, smooth boundary flow are reasonably well classified by the Froude number at low flow; successful allocation decreases as discharge rises and hydraulic diversity within the unit increases. Units dominated by secondary flow, or where velocities are affected by vegetation are poorly classified by all indices. Such units require detailed measurements for their hydraulic characterisation and a new approach to statistical analysis to test the significance of this character.

At higher flows, the Froude number still accurately identifies pool habitats whereas, in general, other units become less distinctive. Thus as hydraulic controls are drowned out, habitat hydraulics at the reach scale are likely to become more uniform. To test this assumption habitat mapping is advocated as a precursor to modelling the impacts of changing flows.

Hydraulic characterisation of morphological units raises the prospect of the habitat hydraulics of changing flows to be synthesised for whole river systems. The national representativeness of study sites may be tested by the River Channel Typology (based partly on morphological units) being compiled by National Rivers Authority field surveyors in England and Wales. This national River Habitat Survey may also form an economical alternative to PHABSIM for extrapolating the measured hydraulic characteristics of reaches.

INTRODUCTION

The need for a more unified classification of instream physical habitats has been emphasised recently by several authors (Jowett 1992, Scruton 1994, Wadeson 1994). Wadeson advocates the term `biotope' as opposed to `habitat', the former referring to community rather than species level. The term habitat is retained to maintain consistency with national inventories, notably River Corridor Surveys and River Habitat Surveys in England and Wales (NRA 1987, 1994). Habitats are distinguished by the hydraulics associated with a particular morphology under a range of flows. PHABSIM estimates of Weighted Useable Area (Shirvell 1989) have indicated the importance of cover in addition to depth, velocity and substrate. Thus a habitat may be defined as *`a morphological unit with a characteristic range of hydraulic, sedimentary and vegetative variables'*.

To provide scale guidance for ecological surveys, catchments may be divided into sectors and reaches; within reaches characteristic morphological units exist (Maddock 1994). A reach is defined as *"a length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occur"* (Wadeson and Rowntree 1994). Selection of representative morphological units and characterisation of their hydraulics allows extrapolation to the reach scale, as channel bed materials within a given reach are relatively constant with fluctuating discharge.

Change in available habitat with discharge is central to the Instream Flow Incremental Methodology. PHABSIM (Physical Habitat Simulation Model) is a computer model which uses a suite of hydraulic and biological models to simulate change in Weighted Useable Area with discharge (Institute of Hydrology 1994). Results are specific to the species and hydraulic conditions of the reach; thus selected to enable general application of simulation results, channels must be classified by reach types (Stalnaker *et al.* 1994). This may permit catchment-scale application, as associated morphological units are known to exhibit unique, yet predictable hydraulic behaviour (Sullivan 1986). Additionally, knowledge of the characteristic hydraulics for a range of discharges within the typical regime will enable water resource managers to evaluate the habitat potential, and assess the ecological impact of land use or proposed flow regimes for a given channel type.

The problem treated by this paper therefore has three dimensions:
a) the subjective selection of reaches and use of nomenclature for morphological units
b) the objective testing of links with dynamic hydraulic properties and processes
c) the use of the geomorphological knowledge base (including physical habitat surveys) to gross up to the catchment for evaluating flow management on, for example, river restoration schemes and in regulated rivers.

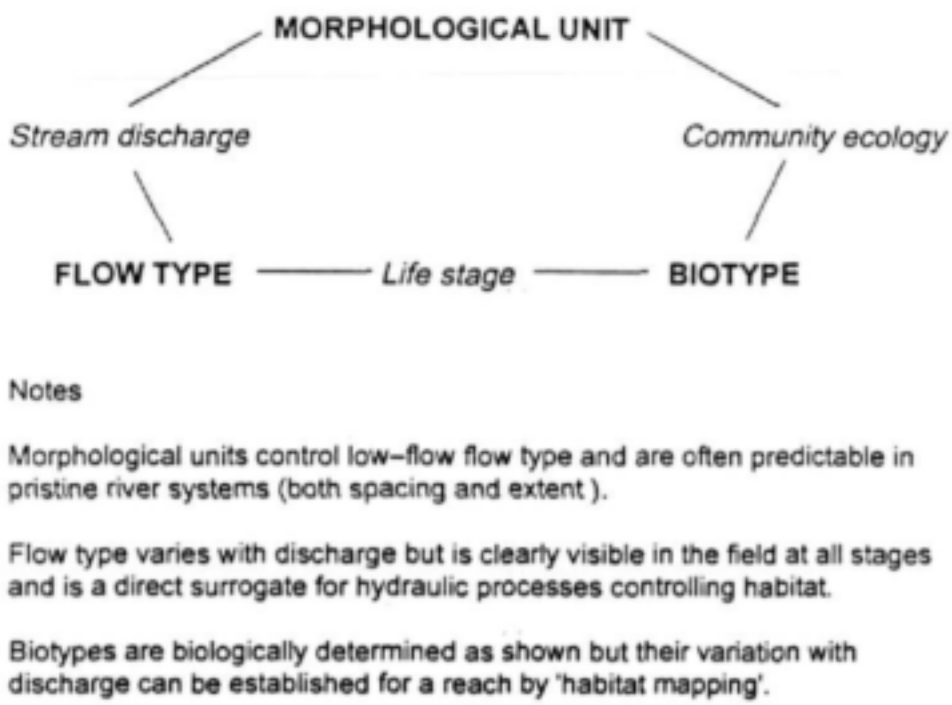

Figure 3.7.1: Aspects of river ecology survey and protection

Channel classification; reach and morphological unit identification

Several attempts have been made to classify rivers into reaches with similar processes to enable appropriate management (Mosley 1987, Kellerhals and Church 1989, Rosgen 1992). The most useful classification system to date is that developed for the US Department of Agriculture and Forest Services (Rosgen 1992), which applies principles of hydraulic geometry (Ferguson 1986) to link morphological channel types and hydraulics. Channels are classified according to topographical, morphological and sedimentary properties, and predictions of hydraulics made for a morphologically defined stream type, based on hydraulic geometry and slope-discharge equations (Leopold and Wolman 1957; Leopold, Wolman and Miller 1964). The relationship between habitat hydraulics and benthic invertebrate zonation (Statzner and Higler 1986) provides an application for the classification: primary production in turn influences fisheries.

The selection of reaches for the present study had to proceed without the benefit of a UK river typology of the type anticipated shortly (NRA 1994). An office-based 'Rosgen-style' classification was attempted for rivers in North East England, but aerial photography cannot identify morphological units. An iterative reach scale classification was adopted, with reaches selected on the basis of two prime geomorphological factors, slope and substrate size. Kershner and Snider (1992) advocate the use of fluvial features as habitat descriptors, including riffles, pools, runs, glides and steps. However no standard techniques exist for their identification across different sectors or reaches. The recent River Habitat Survey (NRA 1994) describes units in terms of flow pattern, width and depth. As these alter with discharge, and absolute dimensions are not transferable between sites, absolute depths are not used. Instead depths described in River Habitat Surveys are considered relative to each other. Discussion with fisheries ecologists and geomorphologists, supported by a literature review and field observation assisted the more disciplined identification of morphological units. These are described briefly in Table 3.7.1. A more detailed description is provided by Wadeson (1994) and his work indicates convergence of views in this field.

Descriptions are also consistent with French terminology, which describes morphological units (Malavoi 1989). Field identification is based primarily on flow type and morphological features as listed in Table 3.7.1. Wadeson (1994) makes the distinction between static, morphological units and the flow-dependent, ecological unit or biotopes. The link between morphological units, biotopes and flow type is illustrated in Figure 3.7.1. From an ecological perspective, it is the combination of morphology and flow dependent hydraulics which contribute to available habitat. At low flows morphological units and biotopes are equivalent; this paper will address the identification of morphological units at the reach scale, and attempt to determine which units are discrete biotopes.

Subjective identification of discrete units can be tested and made reproducible by quantifying easily measurable variables which contribute to physical habitat and which are likely to differ between morphological units. As discharge increases hydraulics will alter according to the influence of morphology on flow dynamics, with biotopes possibly altering and becoming hydraulically more uniform within a reach as individual minor controls drown out. This may be tested by high flow hydraulic measurements and 'habitat mapping', as described later in this paper.

METHODOLOGY

Site selection and field techniques

Channel types were provisionally classified as listed in Table 3.7.1 on the basis of morphological units, dominant substrate and flow type. Study sites representative of each channel type were selected on the basis of proximity to gauging stations, existing monitoring information and access. The final choice of study sites is given in Table 3.7.2 and Figure 3.7.2.

Transect location follows the requirements of PHABSIM (Institute of Hydrology 1994), with modifications to transect spacing depending on longitudinal hydraulic variability. The downstream transect is located at a hydraulic control point, and transects located upstream at intervals of between 5 and 20m, depending on the observed hydraulic variability within a given unit. The aim is to place sufficient transects to record

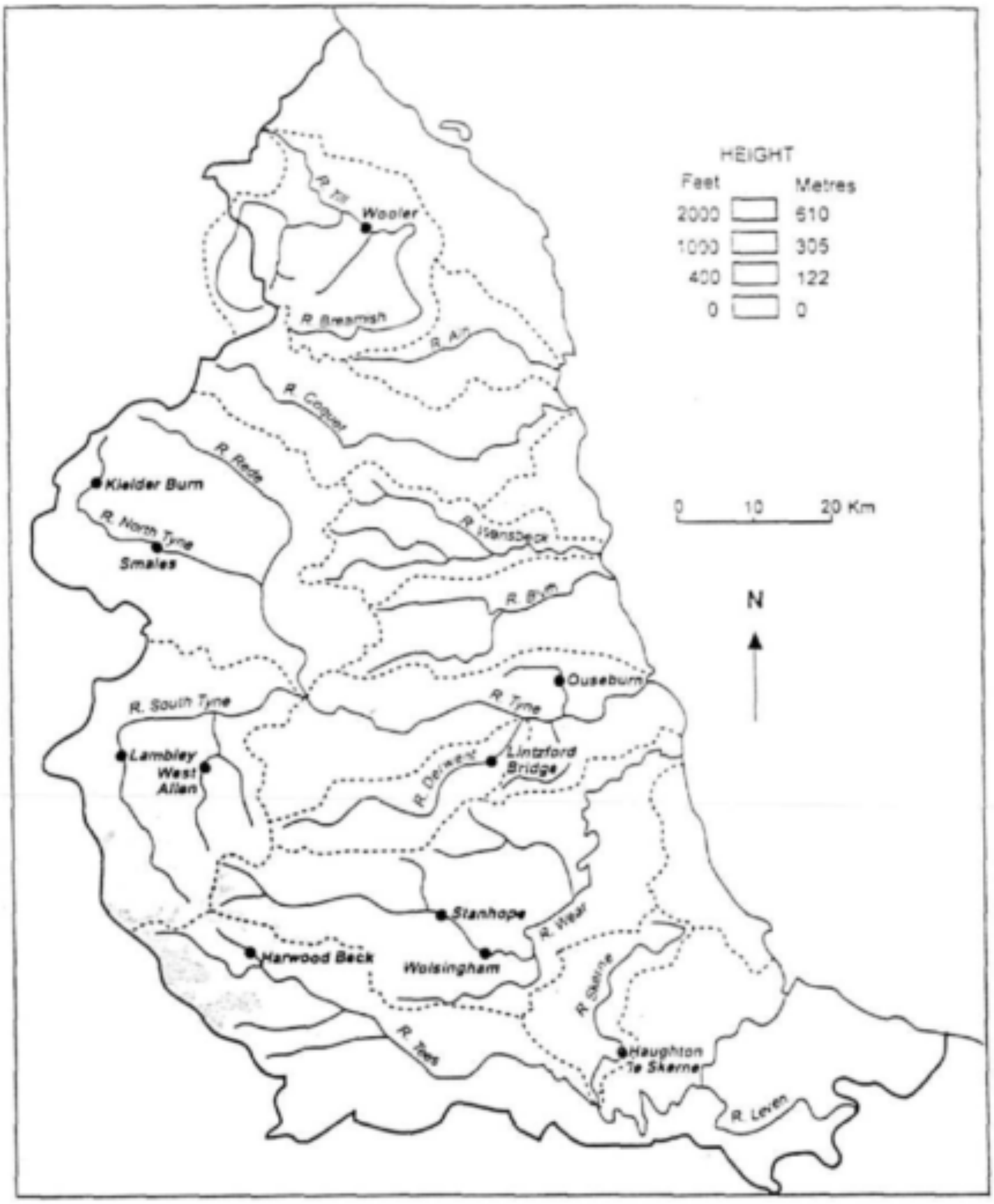

Figure 3.7.2: Study sites within North East England

Table 3.7.1: Observational classification of habitats, by morphology and flow type *(after Allen 1951, Bisson et al 1981, Mosley 1987, Church and Kellerhals 1992, NRA 1994, Crisp personal communication, Campbell personal communication).*

Morphological unit	*Morphological features*	*Flow type and surface patterning*	*Relative depth*
Cascade	Boulders randomly protrude surface	Broken	Low
Step-pool	Boulders organised into steps across channel, separating finer-grained pools	Broken	Low
Rapid	Steep gradient and irregular bed profile	Turbulent whitewater; no protrusions	Medium
Riffle	High points in bed long -profile; sediment size ranges from cobble to gravel	Turbulent; no whitewater or boulder protrusions	Low
Run	Deep, fast flowing water through uniform cross-section. Often local width constriction	Turbulent, unidirectional flow and some standing waves	High
Glide	Deep, moderate flowing water through uniform cross-section	Smooth, unidirectional flow	Medium
Pool	Deep, still section of water between riffle units	Slow or still; horizontal eddies present	High
Slack	As above; extend in excess of 5-7 times channel width	Slow or still; horizontal eddies present	Medium
Backwater	Still region of water attached to main channel at downstream end	Still with horizontal eddies	Low

hydraulic diversity, without data redundancy. Thus transects are located along one complete morphological sequence as described in Table 3.7.2. Their position is marked with wooden pegs or by painting trees or boulders in bedrock reaches. Pegs are numbered to ease location when resampling at other calibration flows. It is recognised that 'within-transect' hydraulic variability can be greater than that in an upstream direction; in headwater streams with log debris and boulders, cross-channel differences account for up to 50% of variation (Sullivan 1986). Thus measurements are taken every metre across the channel, regardless of channel width. This exceeds the sampling density used in River Habitat Surveys, for which ten evenly spaced points proportional to channel width are suggested (NRA 1994). The latter may not fully represent the hydraulics of marginal pools and secondary channels, considered *"the richest biological habitat"* (Church and Kellerhals 1992).

Depth, velocity and substrate size (intermediate diameter) is recorded at each sample point or **cell**, starting from the left bank of the most downstream transect and completing successive transects upstream. Velocity is measured by electromagnetic current meter at 0.6 depth from the surface; however, at sites with seasonal aquatic macrophyte growth or at higher flows in channels with high relative roughness, five profile velocity measurements have been made as part of a study of the validity of our assumptions about

Table 3.7.2: Study sites and low -flow morphological sequence.

Site (Catchment)	*Grid Reference*	*Morphological units present*
Stanhope (Wear)	NY 984 391	C-SP-P
West Allen (Tyne)	NY 781 568	BR-SP-P
Harwood Beck (Tees)	NY 848 310	C-P
Kielder Burn (Tyne)	NY 643 946	C-P-C
Lambley, South Tyne (Tyne)	NY 672 605	P-Ri-P; Bw
Smales, North Tyne (Tyne)	NY 737 857	P-G-Ri
Wolsingham (Wear)	NZ 304 158	Ri-Ru-P-G-Ri
Wooler, River Till (Tweed)	NU 001 307	Ri; P-DRi-P
Lintzford Bridge, River Derwent (Tyne)	NZ 146 571	R(v)-GSP-R(v)-G
Ouseburn (Tyne)	NZ 255 686	S-Ri; P-Ri
Haughton-le-Skerne, River Skerne (Tees)	NZ 304 158	S(v)-R(v)

C=cascade; BR=bedrock riffle; SP=step-pool; Ri=riffle; VR=vegetated riffle; Ru=run; DRi=dynamic riffle; G=glide; GSP=glide plus side pool; S=slack; P=pool; Bw=backwater; (v)=vegetated.

distributions. Sediment sampling at each point also exceeds the minimum data required by traditional methods for substrate size analysis (Wolman 1954). Actual sediment size is measured as opposed to an index based on the Wentworth scale, or that used in PHABSIM (Woody-Trihey 1981), in order to allow sedimentary characterisation of morphological units using data analysis techniques appropriate for continuous distributions.

The effective width (EW) is taken as that section with water present; actual channel width (AW) is also measured as the distance between vegetated banks, or that which is regularly covered under a normal flow regime. This allows EW to be expressed as a percentage of AW, as a simple index of available habitat under fluctuating flows (Maddock 1994).

Stage is recorded at each site, either from permanent stage boards at nearby gauging stations, or from specially installed markers at sites some distance from flow gauges. This allows significant changes in morphology and hydraulics at a site to be related to discharge. Water levels are surveyed at both ends of each transect at all calibration flows to indicate changing energy conditions. Breaks in stage-discharge graphs indicate a significant changes of flow controls (Merrix, personal communication). It does not necessarily follow that significant discharge classes correlate with changes in flow control by morphology and thus habitat hydraulics, but these categories offer an expedient rationale for selecting calibration flows. Sullivan (1986) concluded that habitat hydraulics differed significantly under three flows, notably summer low flow, baseflow and stormflow. To date all eleven sites have been sampled under low flow conditions present between mid June and early August 1994. Ten sites have been sampled at a higher calibration flow, determined by observation of stage and morphological units present. Reference to flow duration curves indicates the probability of these flows occuring annually (Table 3.7.3). Finally morphological units have been mapped using flow types at several of the sites following rainfall 'events', as an indication of channel hydraulics at higher flows. This '**habitat mapping**' is presented under Results and Discussion.

It is worth drawing attention to the unusually high flows which occurred in the North Tyne and River Derwent during the summer of 1994. These may be explained by the fact that both rivers are regulated, so flows are maintained at artificially high levels during drought conditions in order to protect instream habitat or allow pollution dilution and abstractions to continue.

Table 3.7.3: Flow percentiles (exceedence) for study sites, at 'low' and 'moderate' flow

Site	*Low flow Q%*	*Mid flow Q%*
Stanhope, Wear	99.4	98.7
West Allen	97.5	41.0
Kielder Burn	95.4	67.7
Harwood Beck	98.6	57.0
Lambley, S Tyne	96.0	-
Wolsingham, Wear	97.1	82.3
Smales, N Tyne	77.2	26.3
Derwent	81.8	21.7
Ouseburn	99.9	57.1
Skerne	76.0	48.0

Statistical data analysis

The data were processed within the SAS system (SAS 1985), and substrate size distribution calculated for both sites overall and morphological units within sites. Combination indices were calculated for individual cells, including the morphological indices, relative roughness and width-depth ratios. Hydraulic variables calculated are those considered to influence the microhabitat for instream biota, and which have been shown to be good predictors of habitat type. Most notable is the Froude number (Jowett 1992, Rowntree and Wadeson 1994). Froude number *(Fr)* is a dimensionless velocity-depth ratio, allowing comparisons across different rivers. In hydraulic terms it classifies flow as sub-critical (Froude<1) or supercritical (Froude>1) (Davis and Barmuta 1989). This is believed to be a better predictor than the Reynolds number, used to discriminate between laminar and turbulent flow (Chow 1982). In reality laminar flows rarely occur so this index is unlikely to discriminate between morphological units. Ecologically the Froude number provides a relative measure of stresses within the channel, in terms of the range of depths and velocities. The Froude number is calculated by the formula:

$$Fr = Vm / (gY)^{½}$$

Vm = mean water column velocity (ms^{-1})
Y = water depth at a given point (m)
g = acceleration due to gravity (9.81 ms^{-2})

Relative roughness is an index of the effect of substrate size and water depth on hydraulics, calculated by the formula:

$$R = D_{84} / d$$

D_{84} = substrate size of which 84% are finer (m)
d = water depth at a given point (m)

Depth:width ratios were calculated as follows:

$$DW = d / Ew$$

d= water depth at a given point (m)
Ew= effective width ie. wetted width (m)

Depth-width ratio was calculated as an index of channel response to fluctuating flows, for a given degree of entrenchment. By dividing wetted widths and depths a descriptive index of morphological units for a given flow is provided. Depth:width ratios are dependent upon cross-sectional profile, which varies by reach type (Mosley 1987, Kellerhals and Church 1989). It is clear that, under similar flows, entrenched or deeply incised channels will have a greater depth-width ratio than shallow channels with wide floodplains. A rise in discharge will result in a more rapid increase in depth in such channels, with implications for the range of hydraulic variables and hydraulic geometry relations. ***Substrate distributions by site***

Mean substrate distributions were calculated for each site as an statistical indication of gross morphological differences between sites. These are listed in Table 3.7.4.

Analysis of variance (ANOVA) of mean substrate distributions between sites is statistically significant at the 0.001 level. Mean substrate size is an acceptable index of differences in substrate distribution at most sites, with the exception of Harwood Beck. This site has a bimodal substrate distribution of boulders and fine gravels, giving a spurious mean value. Thus D_{84} (the substrate size which 84% are finer than) is suggested as a better index of overall substrate distribution. Additionally it is the D_{84} which has most influence on flow resistance (Maizels 1984); thus it is more likely to correlate with flow hydraulics. The next stage of analysis looks in more detail at morphological units, which under low flow conditions, are equivalent to biotopes.

Table 3.7.4: Mean substrate size (D_{50}) of study sites

Site	***Mean substrate size (mm)***
Stanhope, Wear	335
West Allen	278
Kielder Burn	167
Lambley, S. Tyne	133
Smales, N. Tyne	119
Harwood Beck	116
Wolsingham, Wear	101
Derwent	75
Ouseburn	39
Till	26
Skerne	0.9

Discriminant analysis: objective classification of morphological units

Each transect was subjectively assigned to a particular morphological unit, and coded in SAS to allow indices for individual cells to be averaged at the scale of the morphological unit. In addition to the hydraulic variables recorded, substrate distributions, Froude numbers, relative roughness values and depth-width ratios were averaged for each morphological unit within a given site.

Discriminant analysis provides an objective, statistical test of classification into morphological units. It works by assigning each cell to a particular type or morphological unit, on the basis of its associated hydraulic variables. The choice of variables on which discriminant analysis allocates cells to a particular type is subjective. In this case the three indices listed above were used; being dimensionless they allow data from different rivers to be compared. The aim of discriminant analysis is to ascertain which 'habitat indices' most successfully predict morphological units. Indirectly it also provides an indication of which units are similar on the basis of a given index. For example 60 % of cells coded as glides may be correctly allocated as glide, with the remaining 40 % being classified as run. Thus it may be inferred that runs and glides are similar in terms of their Froude numbers.

Discriminant analysis produced many misclassifications when attempted across the ***range of channel types***. This confirms the variability between the habitat hydraulics of identical morphological units in different reaches and at different flows. However if ***individual sites*** were taken as representative of a given reach type and ***river specific*** disc+riminant analysis performed, a greater proportion of 'habitat units' were successfully classified. Results are summarised in Tables 3.7.5 and 3.7.6, for low and moderate flow respectively.

RESULTS AND DISCUSSION

Allocation to morphological units by discriminant analysis

Table 3.7.5: Percentage of morphological units correctly classified by discriminant analysis of Froude number (plain text), relative roughness (bold italics) and depth:width ratio (bold) under LOW FLOW conditions. Index listed is that which correctly classifies the greatest percentage of cells to a given morphological unit.[1]

Flow Type	**A**			**B**		**C**		**D**		
Site	*Cascade Step pool*	*Riffle*		*Run*	*Glide*	*Dynamic*	*Glide-side pool*	*Pool*	*Slack*	*Back-water*
Stanhope	***59.7***		***63.6***					100		
West Allen		***79.1***	***70.0***					100		
Harwood Beck	42.6							**81.8**		
Keilder Burn	***67.5***							**81.5**		
Lambley		***100.0***						**76.5**		71.4
Smales		***94.8***			100.					
Derwent		***72.0***			77.8		74.4			
Wolsingham		***88.2***		***57.0***	37.7			70.0		
Till		***71.8***		***47.6***	60.0	**24.1**		**82.3**		
Ouseburn		***92.1***						25.0	**90.0**	
Skerne		***75.0***						81.8	**76.8**	

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[1]Subsequent analyses, reported by Padmore *et al.* (in press) have utilised biotope classification and hydraulic data at the cell level, giving much stronger relationships which, unlike the results reported here, are not river specific and can be more successfully generalised.

If 75% or more observations are accurately classified for a given morphological unit, the index may be accepted as a good predictor of habitat type. This is an arbitrary cut-off level, selected partly on the basis of similar work in New Zealand rivers (Jowett 1992). Approximately 65% of riffle, pool and run units were accurately classified using the Froude number; this was considered an acceptable margin of error.

At low flow, depth:width ratio is more successful than the Froude number in classifying riffles and cascades. The Froude number is a poor predictor of morphological units with turbulent, rough boundary flow for three possible reasons: firstly a high range of velocities exist, from negative values to exceptionally fast 'threads' associated with supercritical flow over boulders. Secondly at the exceptionally low flows under which data was collected, supercritical flows were rare, so habitat hydraulics were similar to other units in the reach. For example at Harwood Beck, although cascades could be distinguished from pools by presence of large boulders, the units were similar in terms of flow type. Finally, Froude values are calculated from velocity readings taken at 0.6 depth, which in rough boundary conditions are not necessarily representative of average velocities for that morphological unit (Bathurst 1988). This is true for vegetated riffles also; detailed velocity profiles recorded on the River Skerne show a deviation from the semi-logarithmic distribution (Padmore, unpublished). Only for Smales and the Ouseburn does the Froude number correctly allocate more than 65% of cells, which suggests a narrower range of Froude numbers exist in such riffles.

Pools are successfully classified by the Froude number; this reflects the uniform, slower flowing units which require fewer velocity readings to accurately characterise them. The Froude number correctly allocates the majority of cells in pools of boulder dominated reaches. Pools in sites with intermediate size

Table 3.7.6: Percentage of morphological units correctly classified by discriminant analysis of Froude number (plain text), relative roughness (bold italics) and depth:width ratio (bold) under MODERATE FLOW conditions. Index listed is that which correctly classifies the greatest percentage of cells to a given morphological unit.

Flow Type	A			B		C		D		
Site	*Cascade*	*Riffle*	*Step pool*	*Run*	*Glide*	*Dynamic*	*Glide-side pool*	*Pool*	*Slack*	*Back-water*
Stanhope	***97.8***			***50.0***						
West Allen		65.5						100		
Harwood Beck	***68.2***							79.2		
Keilder Burn	***58.5***							**81.5**		
Lambley								77.4		
Smales				***80.7***	83.8					
Derwent		60.9			50.0		**70.8**			
Wolsingham		***83.6***	***53.6***	15.9	**84.0**			**70.0**		
Till		***23.1***	56.5		17.9	7.1		**94.9**		
Ouseburn		***66.7***						**86.6**	***59.2***	
Skerne		***100***						**100**	**98.8**	

substrate distribution or fine grained gravel beds are most successfully classified by relative roughness. Units with turbulent, smooth boundary flow are reasonably well classified by the Froude number, whereas units where secondary flow dominates are poorly classified by all indices, due to their complex hydraulics. This necessitates careful field identification by flow type as listed in Table 3.7.1, and detailed velocity profiles in order to accurately describe their hydraulics.

At moderate flows the Froude number is a poor predictor of morphological unit, except where ponded or uniform flow occurs. Relative roughness is the most successful index for pools at sites with smaller substrate size distributions, as this value will become more uniform within the unit as depth increases.

Units are less successfully classified by any of the three indices than at low flow, which suggests greater hydraulic similarity between biotopes in a given reach. This reflects the 'drowning out' of morphological flow controls at higher discharges. Only Harwood Beck and the West Allen have a greater percentage of correct classifications at moderate flow; at these sites increased discharge leads to turbulent, supercritical flow over boulders in cascade units. At very low flows there was not sufficient depth or velocity for this to occur; drought conditions of a 1 in 10 or 20 year return period were present during July - August this year (Archer, personal communication), so cascade or riffle units were hydraulically similar to pools.

Observations at Harwood Beck and the West Allen compared to other sites raise the concept of **'threshold flows'**. A threshold flow may be defined as that discharge which causes increased hydraulic diversity between biotopes. As flows increase in cascades hydraulic diversity is initially increased as supercritical flow occurs over boulders. However, with further increases in discharge and depths greater than the average height of boulders, flow type will become subcritical (evident when boulders are submerged and the surface profile becomes more even). One objective is to establish the discharge under which biotopes change in different reaches, or alternatively to characterise the broad hydraulic response of morphological units within a given stream type. This is being attempted by **habitat mapping**, as discussed below.

Habitat mapping of high flows

The purpose of this paper is not to provide detailed information on the hydraulics of different reaches under different flows; these are not yet being modelled by PHABSIM because of insufficient calibration flows. Instead an indication of channel response to increased discharge at the scale of the morphological unit is provided by **habitat mapping**. Sites were observed under different flows, stage levels recorded and biotopes mapped. This involved sketching flow type onto a base map of the site, supported by photographs at each transect and any change in flow type. By repeating habitat mapping after storm events it may be possible to determine **threshold flows** ie. discharges which bring about a fundamental change in biotope distribution. A selection of sites which have been mapped is listed in Table 3.7.7.

In ecological terms, quantification allows hydraulic characterisation of both 'representative' and 'critical' reaches. The former includes the sequence of morphological units which are repeated in a given sector (Maddock 1994) or reach (Wadeson and Rowntree 1994). It is to the hydraulics of these units at low to mid flows that biological populations will be adapted, as these flows occur at critical species' life stages. Critical reaches include those units which occur infrequently in the catchment overall (Petts and Maddock 1994). King and Tharme (1993) give critical units special ecological significance, considering them *"absolutely essential for the completion of one or more life stages of the selected target species, but which are poorly represented in the reach"*. It is clear that conservation of habitat hydraulics by appropriate flow manipulation is paramount for such reaches.

Table 3.7.7: Comparison of biotopes under low and high flow (high flow observed on 4 August 1994, following an intense storm the previous evening).

Site	*Sequence of morphological units under low flow*	*Sequence of biotopes under high flow*
Harwood Beck	Pool-cascade	Rapid
Wear at Stanhope	Pool-step pool-cascade	Chute-rapid
Lambley	Pool-riffle-pool	Glide-rapid-run
Kielder Burn	Cascade-pool-cascade	Rapid-run-rapid
Smales	Riffle-glide-pool	Glide
West Allen	Pool-step pool-cascade	Pool-run

CONCLUSIONS

The work reported here was embarked upon with the triple aims of characterizing biotopes by their morphological controls and flow type, assessing the hydraulics of the units thus delimited and testing the applicability of the outcomes to river habitat surveying, and eventually, the setting of ecologically acceptable flows. Morphological units have been identified in the field by their characteristic morphology and flow type. By statistical analysis the subjective classification has been tested and refined, to identify units with discrete hydraulics for a given flow. Initially this has been undertaken at low flow, when cross-sectional morphology and substrate have maximum influence on hydraulics via flow resistance. We are, as yet, far from establishing all the links, but the following points are clear:

1. Units with turbulent, rough boundary flow are best classified by depth:width ratio. The Froude number is less successful because of the hydraulic diversity associated with such units. Detailed hydraulic descriptions are required and consideration given to alternative indices for their characterisation.

2. The Froude number successfully identifies units with turbulent, smooth boundary flow. Either Froude numbers or relative roughness values may be used to identify pools.

3. Descriptive indices based on '0.6 depth' values for a given morphological unit provide limited hydraulic information in units which lack the classic semi-logarithmic velocity profiles. These include boulder bed cascades, vegetated channels and units where secondary flows dominate. Detailed velocity profiles are needed for such reaches. In vegetated channels we are performing three calibration gaugings in **both** the vegetated and unvegetated seasons of the year.

Despite debate over which are the most appropriate statistical techniques and 'habitat discriminating indices' on which to test the subjective qualitative classification of morphological units, preliminary results are consistent with similar work in New Zealand and South African rivers. Thus subjective field identification of habitat units in bedrock and alluvial reaches of rivers in North East England, by description of morphology and flow type, may be accepted as standard procedure for habitat identification. Thus, in future all the main predictive techniques, including PHABSIM, can utilise our growing convergence of view on the characterisation of channels. Mid- and high- flow hydraulic characterisation and habitat mapping will provide information on habitat hydraulics in a usable form over a timescale relevant to water resource managers (e.g. in environmental impacts assessments).
In terms of guiding habitat surveys this study clearly indicates the value of both inventories of morphological units ***and*** flow types (with the latter as a guide to the former). These should be the basis of channel typologies specifically aimed at describing the gross habitat hydraulics and flow sensitivity of river networks. If such inventories and typologies are successful they provide a major alternative means of

characterizing the impacts of, for example, river regulation or climate change to the more demanding and expensive instream methodologies such as PHABSIM. Even in their absence, the significance of morphological units as indicators of habitat hydraulics means that conventional at-a-site and downstream hydraulic geometries, rendered 'unit-specific', would be a useful reconnaissance method of catchment wide habitat appraisals.

Our main methodological conclusions mean, however, that optimism must be tempered in relation to field measurement in very rough channels and those with a seasonal growth of aquatic macrophytes, in relation to the ability of statistical tests to use all the field information and in the characterisation of some flow types (e.g. those dominated by secondary cells).

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4. DISCUSSION

The following three groups of questions were discussed by the participants.

1. What is the ecological significance of a physical biotope?
   Is it an appropriate scale for studying ecological structure and functioning ?

2. Is the biotope best identified by hydraulic conditions, specifically flow type ?
   How can substrate be incorporated?

3. How should representative sites be selected and how can we extrapolate from one site to another?

1. What is the ecological significance of a physical biotope ? Is it an appropriate scale for studying ecological structure and functioning ?

In his starter paper Roy Wadeson defined the biotope as "a spatially distinct in-stream flow environment characterised by specific hydraulic attributes". The scale of the biotope lies within the range of circum one metre up to one channel width, depending on the channel form and the uniformity of flow conditions across the channel. The aim of the workshop was to assess whether the biotope was a useful unit for the purpose of river management. Two related questions arise, the question of ecological significance and the question of scale. Jay O'Keeffe opened the discussion with the comment that the ultimate but unrealistic goal of ecological research is a complete understanding of biological systems and their interrelationships at all scales. Within one biotope there may be significant variation: it was suggested that a pool\riffle\run biotope sequence has tremendous variability both within as well as between biotopes. Intensive sampling is required in the riffle due to the concentration and diversity of species there. Riffle populations tend to be position specific ie. top\underneath of cobbles and should perhaps be studied at the scale of the individual cobble rather than the biotope. Because of this heterogeneity, Jay O'Keeffe also questioned whether it is possible to rigorously measure community diversity and abundance at the biotope scale.

After a general discussion it was agreed that the biotope scale undoubtedly has ecological significance, but not necessarily more so than any other scale. It is, however, a practical unit of data collection that can be recognised by both geomorphologists and ecologists and it is the finest scale at which both disciplines can conveniently work together, being the smallest scale at which geomorphologists can work and possibly the coarsest acceptable to ecologists studying population/community dynamics. It is also the scale at which realistic and reliable hydraulic predictions can be made; moreover PHABSIM can be applied effectively at that level. The use of ecologically acceptable biotopes defined by their geomorphological characteristics would seem to be an acceptable compromise between practicality and scientific requirements. Intrinsic variability within biotopes must however be recognised. A further advantage of the biotope scale is that it allows the synthesis of large river systems from detailed site investigations. The biotope is the smallest unit in Wadeson and Rowntree's hierarchical framework for categorising river systems.

At this point it was felt necessary to clarify the definition of a biotope as given earlier by Roy Wadeson. It was agreed that the correct term should be `physical biotope', thus excluding any effects of the biota themselves on habitat conditions. The supposed association between physical biotopes and communities was also questioned. It was suggested that physical biotopes should be related to species assemblages rather than communities as this did not presume the dominance of species interactions in governing the presence/absence of populations.

The following arguments were raised in support of these points.

- Habitat defines the environment of a species which results from physical, chemical and biological interactions.

- Biotope defines the environment of a species assemblage, which results from physical, chemical and biological interactions.

- The term biotope as used in this workshop is based purely on physical factors; 'physical biotope' is therefore more appropriate.

- 'Physical biotope' would be in accordance with PHABSIM which uses the term 'physical microhabitat'.

- The general model of succession for ecosystems assumes that as a pioneer species *assemblage* develops through a secondary to a climax *community* the environment is modified to allow the entry of new species. At the climax stage biological interactions control the community.

- In South African rivers it would seem that the physical factors continue to exert a control because of the episodic and unpredictable nature of our fluvial systems, denying assemblages the chance to develop through to climax communities.

- The lack of biotic controls associated with climax communities may point to a greater importance of physical controls, and hence of physical biotopes, in determining species distributions.

- 'Assemblage' should be used rather than 'community' as the term does not assume any interaction between organisms; South African aquatic organisms may well be considered as assemblages rather than communities due to controls determined by the physical nature of South African rivers.

2. Is the physical biotope best identified by hydraulic conditions, specifically flow type ? How can substrate be incorporated ?

If the physical biotope is accepted as the finest practical scale for management purposes it is important that biotopes can be recognised through consistent field criteria. In the biotope concept it is assumed that the interaction of flow hydraulics and substrate determines the physical environment experienced by the biota at this scale. This raises the question as to what hydraulic variables influence ecological processes and how. Do velocity, turbulence, viscosity and so on have any significance in terms of living organisms? Discussions on flow-related criteria gave rise to the following thoughts.

Flow distributes food and oxygen, scours out sediment and keeps rock surfaces free of fine silts or algae. In cobble beds benthic organisms live both on top of and underneath stones. Stability of the substrate under different flows is important. Near-bed hydraulics related to depth of the laminar sub-layer and boundary shear stress may be the critical variables. For fish, flow depth and velocity profiles are probably more important than near-bed conditions and substrate (except when spawning). Because hydraulic enclaves such as backwaters are important for hydraulic cover, the spatial distribution of hydraulic conditions should be considered.

Physical biotope types can be related not only to hydraulic conditions, but also to sedimentation characteristics. A riffle by nature is clean and free of fine sediment, even at low flows, whereas runs have more variable sediment conditions. Under good catchment conditions with low silt production, cobbles would be clean and well populated with animals. Where sand or other fine material dominates the sediment load, smothering of cobbles may reduce available habitat for stream organisms. At low flow a run may become clogged, needing flushing flows to maintain its physical diversity. Pools are areas where fine silts and organic detritus tend to accumulate.

It was agreed that these flow hydraulics represent a highly complex mix of conditions for which a simple surrogate may be needed. Malcolm Newson suggested a subjectively defined flow type as a useful index, explaining its usage in Catherine Padmore's studies and its recent extension to national surveys in England.

Flow type is determined primarily from the appearance of the water surface, which may vary from smooth through rippled to broken with standing waves. Definitions of different flow types as agreed by the workshop participants are given in Table 4.1a. Flow type is thought to be directly related to the Froude

number of the flow and to boundary roughness. It thus takes into account the interaction of flow velocity, flow depth and substrate size, all variables deemed to be of ecological significance.
Although bed conditions have a direct effect on flow type through the development of turbulent eddies, flow type does not distinguish directly between different substrates. Substrate size class (Table 4.1b) needs to be considered in its own right due to its important role in determining habitat and hydraulic cover. For example bedrock has a low surface heterogeneity and thus low numbers and diversity of organisms. Cobble beds, with good hydraulic cover and a variety of habitats, may have between 1000-20 000 invertebrates/m^2 whereas a sand bed less than 1000/m^2 because of its unstable and uniform character. Thus, although a useful index of hydraulic conditions, flow type is not sufficient on its own to define a physical biotope.

Through combining flow type and substrate class in a matrix (Figure 4.1) an objective method was initiated for visually identifying and defining the biotopes that had hitherto intuitively been recognised by ecologists. The matrix was modified after field testing in a small tributary of the Olifants River which provided a wide range of hydraulic conditions. It seemed to be of sufficient promise to warrant further research and testing. More detailed descriptions of physical biotopes recognised by the workshop participants are given in Table 4.1c.

It should be noted that subsequent to the workshop Mr Wadeson has adopted the term hydraulic habitat in place of physical biotope. This avoids the possible implication that physical habitat incorporates water quality variables such as water chemistry and temperature.

Table 4.1. Definitions of flow types, substrate types and biotopes as used in the physical habitat matrix

a. Flow types

No flow	no water movement
Barely perceptible flow	smooth surface, flow only perceptible through the movement of floating objects.
Smooth boundary turbulent	the water surface remains smooth; streaming flow takes place throughout the water profile; turbulence can be seen as the upward movement of fine suspended particles.
Rippled surface	the water surface has regular disturbances which form low transverse ripples across the direction of flow; the degree of disturbance may vary from faint ripples to strong ripples.
Undular standing waves	standing waves form at the surface but there is no broken water.
Broken standing waves	standing waves present which break at the crest (white water)
Free falling	water falls vertically without obstruction.
Chaotic flow	complex mixture of continuously varying flow types associated with unsteady, pulsating flow; common at high flows.
Boil	the direction of flow is predominantly vertical, with strong horizontal eddies; boil forms on the surface of the water.

b. Substrate (Wentworth scale)

Substrate class	Particle diameter (b-axis)
Silt	< 0.0625
Sand	0.0625 - 2
Gravel	2 - 64
Cobble	64 - 256
Boulder	> 256
Fractured bedrock	bedrock with significant cracks and crevasses which afford some cover.
Smooth bedrock	bedrock lacking cracks or crevasses.
Cliff	a vertical bedrock face

c. Physical biotopes

Pond/ standing pool	this is a detached body of water which lacks any current. It may form on any substrate where there is a hollow sufficient to retain water.
Backwater	A backwater is morphologically defined as an area along-side but physically separated from the channel, but connected to it at its downstream end. Water therefore enters the feature in an upstream direction. It may occur over any substrate.
Dead zone	A dead zone is an area of no perceptible flow which is hydraulically detached from the main flow but is within the main channel. It may occur at channel margins or in midchannel areas downstream of obstructions or secondary flow cells. It may occur over any substrate.
Pool	A pool is in direct hydraulic contact with upstream and downstream water but has barely perceptible flow.
Glide	A glide exhibits smooth boundary turbulent flow, with clearly perceptible flow without any surface disturbance. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Thus glides could only occur over cobbles at relatively high flows. Flow over a glide is uniform such that there is no significant convergence or divergence.
Chute	Chutes exhibit smooth boundary turbulent flow at higher flow velocities than glides. They typically occur in boulder or bedrock channels where flow is being funnelled between macro bed elements. Chutes are generally short and exhibit both upstream convergence and downstream divergence.
Run	A run is characterised by a rippled flow type and can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. It may be useful to distinguish fast and slow runs in terms of the degree of ripple development. A fast run has clear rippling, a slow run has indistinct ripples.
Riffle	Riffles may have undular standing waves or breaking standing waves and occur over coarse alluvial substrates from gravel to cobble.
Rapid	Rapids have undular standing waves or breaking standing waves and occur over a fixed substrate such as boulder or bedrock.
Cascade	A cascade has free-falling flow over a substrate of boulder or bedrock. Small cascades may occur in cobble where the bed has a stepped structure due to cobble accumulations.
Waterfall	A waterfall has free falling flow over a cliff, where a cliff represents a significant topographic discontinuity in the channel long profile.
Boil	A boil flow type may occur over any substrate

N.B. It is suggested that biotopes can be recognised in the field by a combination of their flow type and substrate class e.g cobble or gravel riffle, sand or boulder run.

It should be noted that the above definitions do not consider other ecologically significant biotopes such as undercut banks and marginal vegetation which, while recognised as being important, were considered to be a separate issue outside the scope of the workshop.

The Physical Biotope Matrix

SUBSTRATE

Silt	Backwater	Pool	Glide					Boil
Sand	Backwater	Pool	Glide	Run			Mixed	Boil
Gravel	Backwater	Pool	Glide	Run	Riffle		Complex	Boil
Cobble	Backwater	Pool	Glide	Run	Riffle	Cascade	mosaic at	Boil
Boulder	Backwater	Pool	Chute	Run	Rapid	Cascade	very high	Boil
Fractured bedrock	Backwater	Pool	Chute	Run	Rapid	Cascade	flows	Boil
Smooth bedrock	Backwater	Pool	Glide	Run	Rapid	Cascade	Mixed	Boil
Cliff						Waterfall		
	No flow	***Barely perceptible flow***	***Smooth & turbulent***	***Ripples***	***Undular or breaking standing waves***	***Free falling***	***Chaotic flow***	***Vertical flow***

FLOW TYPE

Figure 4.1 Biotope matrix based on flowtype and substratum

A field visit was made to a tributary of the Olifants River which is known to have several endemic fish species. The reach was identified as having a planar boulder bed, the substrate being dominated by small boulders and cobble distributed in a disorganised manner, with no distinct patterns such as pools and riffles that could be related to hydraulic forces.

Field testing confirmed the usefulness of the biotope matrix, although a number of questions remained. These related particulary to pools. Jay O'Keeffe argued for a further subdivision of pools based on depth of pool and residence time of the water, but it was felt such a distinction was beyond the scope of the workshop. There was also a lack of consensus regarding terminology for isolated pools and the distinction between backwaters and deadzones.

The question of the appropriate scale for physical biotope identification also raised debate. Flow types are observed over an area whereas hydraulic measurements are made at a point. Ecological studies are usually carried out at the particle scale (cobble). These point studies therefore need to be contextualised within the aerial physical biotope unit. It was also evident that definitions must not be scale dependent if they are to be widely applicable.

3. How should representative sites be selected in an IFR exercise and how can we extrapolate from one site to another?

The discussion started by addressing the purpose of the `representative reach' in an IFR exercise. Should the reaches be representative or critical? It was pointed out that in an IFR exercise the selection of sites is limited by the strict time and resource constraints which force researchers to a) identify zones of rivers for which individual assessments should be made and, within them, b) choose reaches, sites and transects that are as representative as possible of those zones. Such sites and transects tend to be chosen for their ecological significance (e.g. riffles) or for their naturalness as this provides clues as to past natural flow regimes. An example would be the zonation of riparian trees reflecting inundation patterns.

It was agreed that sites should be natural: they should be representative of undegraded conditions, with relatively natural attributes and, if maintained correctly, should allow the upstream channel to achieve the desired future state.

The IFR attempts to identify target sites for management. Riffles are often selected as target sites as they are affected first by a change in flow; they also provide the most diverse habitats. Pools are maintained in some state even during negligible flows. In practice sites are often selected for the wide range of morphological units and physical biotopes which are contained within a small area, rather than for the degree to which they represent the wider area.

From the general discussion it was agreed that the method used for site selection in IFR procedures is based on pragmatic considerations rather than sound scientific principles. It was proposed that the more holistic approach adopted by geomorphologists, using the biotope as the smallest morphological unit within an hierarchical catchment system, might offer a practical solution by which the target sites can be better related to both the local reach and wider catchment conditions.

Kate Rowntree presented an example from the Sabie catchment to illustrate how the hierarchical approach being developed at Rhodes University could assist in both site selection and extrapolation. The method is based on the assumption that river processes are ultimately controlled by catchment scale forces which determine streamflow and sediment inputs. It therefore takes a top down approach, identifying sediment and runoff source areas, channel segments, reaches, morphological units and, at the finest scale, biotopes. The method facilitates the selection of representative reaches within which target sites can be selected. Extrapolation from the target site to the river network should be facilitated. It was agreed that this provided a logical approach in South Africa where there are few data on the morphology of our rivers at the level of the morphological unit or biotope.

Malcolm Newson described the alternative approach which is being adopted by the National Rivers Authority (England and Wales). A study has been initiated which will provide a comprehensive typology of channels based on channel, sector and catchment type. A network of 5000 sites will give a sampling density of 3 sites per 10 km of channel for the whole of England and Wales. At each site a 500 m stretch of river will be surveyed using transects at 50 m intervals. The data that is collected at each transect is largely gathered from visual observation to give a qualitative assessment of river condition. From this will be developed a habitat quality index as demanded by the Directive on Ecological Quality of Surface Waters. The survey will also furnish much valuable data relating to the geomorphological characteristics of the rivers. This should be invaluable as a basis from which to make future site selection and extrapolation for IFR-type work. The typologies resulting from the River Habitat Survey data will enable predictions of biotope number/ location for each of about 11 channel types - a means of modular extrapolation of habitat hydraulics.

Manpower requirements for such a study are considerable. A preliminary study of 1500 sites took 40 man-months. Such a study for South Africa is obviously inappropriate given both the size of the country, the inaccessibility of much of the terrain and the lack of trained field workers. A more practical approach is to use the top-down hierarchy for specific river systems of interest.

4. Application of physical biotope mapping to at-a-site IFR assessment

A fundamental question that remains, whichever approach is taken, is whether the relationship between physical biotopes and morphological units can be utilised in the IFR procedure and perhaps provide a more effective means of modelling the effects of changing flows. There are two underlying premises which need to be examined further. The first is that a given class of morphological unit will have particular physical biotopes associated with it. The second is that, whereas morphological units are stable features (except under extreme flood events), physical biotopes are discharge dependent. Thus at low flows a morphological pool will be dominated by pool biotopes, but runs may be present at the upstream transition to a riffle. At higher flows the upstream run will extend further into the pool and may come to dominate it. Padmore *et al.* (this report) suggest the application of 'biotope mapping' to develop techniques for predicting characteristic changes with increasing flow (i.e. changes of biotope extent or position).

These relationships are being explored independently for South African rivers by Roy Wadeson (with Kate Rowntree) and for English rivers by Catherine Padmore (with Malcolm Newson). If, as appears to be the case from preliminary results, these two groups find consistent relationships between substrate, hydraulic indices, flow types, physical biotopes and morphological units, *and these can be shown to have ecological significance*, it opens the door to a new approach to IFR and PHABSIM type modelling. The following procedure is suggested as an alternative or complimentary methodology:

1. Identify the significant morphological units in the reach of interest; this can be done relatively rapidly using a mixture of aerial and ground surveys.

2. Select a range of morphological units for further study, in particular to observe physical biotope dynamics over a range of discharges.

3. At each discharge map the distribution of flow types and associated substrate in order to assess the proportion of different physical biotopes in each morphological unit.

   If, as has been indicated, the flow type - substrate combination can be used as an index of the complex hydraulic conditions relevant to the stream biota, it may not be necessary to take time consuming depth and velocity measurements at each site. Rather, time could be spent on surveying a larger number of sites so as to better encompass the complexity of most natural river systems.

4. Repeat the above observations at a range of discharges.

5. Utilise the above information on changes in physical biotope distribution with discharge to model the effects of different flow levels on available habitat.

6. Carry out a biological survey using the physical biotope as the spatial sampling framework.

The above procedure promises to provide a more efficient and meaningful approach to assessing low flow requirements than the use of hydraulic models on their own. Physical biotope mapping could be used either in conjunction with, or even in place of, hydraulic estimates made for line transects. Before this can take place, however, further research is needed to authenticate the assumed relationships. Although the work of Roy Wadeson and Catherine Padmore should go some way to elucidating the relevant physical relationships, further research will be needed before effective management tools can be developed for different river environments. Fundamental ecological research is also required to test whether the distribution of stream fauna is in fact related to the visually identified physical biotopes, and whether the faunal response to changes in flow in any way mirrors the apparent change in physical biotope. Absence of any relationship would negate the whole approach.

Co-operation between the separate groups of researchers will be extremely helpful in developing basic concepts, but from field experience during the workshop it was evident that the considerable differences between U.K. and South African rivers will prevent the direct transfer of empirical relationships between geographical areas.

5. Further research

The workshop was invaluable in bringing together scientists both from different continents and from separate disciplines. Firstly, the workshop underlined the convergence of approaches to instream flow assessments being developed in both South Africa and England and Wales and pointed to the potential that exists for co-operation in developing these methodologies. Secondly, the workshop provided an opportunity for geomorphologists, ecologists and hydraulic engineers to work towards a collective understanding of instream flow needs. A particular achievement was the adoption of a common terminology relating biotope to flow type and substrate. The next steps are to place this relationship within the framework provided by the channel morphology and to confirm the ecological significance of the physical biotope. A clear need was expressed for co-operative research between geomorphologists and ecologists.

6. Recommendations

1. Co-operative research between ecologists and geomorphologists is needed in order to assess the ecological significance of physical biotopes. In particular the following aspects need to be addressed or investigated further:

    - clarification of definitions of morphological units and physical biotopes
    - quantification of flow types and physical biotopes in terms of substrate, flow hydraulics and hydraulic diversity (ongoing)
    - assessment of the relative abundance of different physical biotopes in relation to morphological units (ongoing)
    - comparison of biotic assemblages within and between physical biotopes (initiated)
    - identification of critical physical biotopes by ecologists so that geomorphologists can focus hydraulic research

2. Development of improved instream flow methodologies should be encouraged through collaboration between the two groups of scientists from the UK and South Africa.

3. A partial inventory of South African rivers should be initiated through encouraging river scientists to collect appropriate data on all site visits. A data form has already been prepared and field tested by Roy Wadeson, together with others. Further modification may be required in response to the findings of this workshop. In order to standardise data collection it is recommended that a workshop is held at which scientists can assess the data form, discuss its application and be introduced to the methodology. A data collection and retrieval system should then be set up.

4. A library of pictures of channel types, morphological units, biotopes and flow types should be established in order to facilitate identification and communication of terms between scientists.