The Structure, Function and Management Implications of Fluvial Sedimentary Systems (Proceedings of an international symposium held at Alice Springs, Australia, September 2002). IAHS Publ. no. 276, 2002.

Development of a method to assess ecological impact due to hydrological regime alteration of Scottish rivers

ANDREW R. BLACK, OLIVIA M. BRAGG, ROBERT W. DUCK & JOHN S. ROWAN

Environmental Systems Research Group, Department of Geography, University of Dundee, Dundee DD1 4HN, UK

e-mail: r.w.duck@dundee.ac.uk

Abstract The Water Framework Directive (WFD) of the European Union is the principal driver behind the development of protocols for the assessment of anthropogenic impacts on the hydrology of Scotland's rivers, lakes and transitional waters. A new approach for rivers, known as the Dundee Hydrological Regime Assessment Method (DHRAM) has been developed. The underlying rationale is to assess the risk of significant impact on biota arising from changes in hydrological regime, as distinct from chemical or hydromorphological influences. This approach is based on the Indicators of Hydrologic Alteration (IHA) methodology of Richter *et al.* (1996), in which the degree of alteration of a range of hydrological variables that are significant to biota are estimated. The DHRAM method classifies the degree of alteration to hydrological regime using a five-point scale, which correlates with the risk of ecological damage. These categories are compatible with those of the WFD. The acquisition of appropriate biological data for calibration and validation of DHRAM has, however, proved problematic. This paper proposes the future development of a calibration scheme which compares the biota of neighbouring water bodies (pairs whose physical attributes are as similar as possible in all relevant respects, except in the degree of disturbance to their hydrological regimes).

Key words Water Framework Directive; European Union; hydrological regime alteration and assessment; ecological quality; DHRAM (Dundee Hydrological Regime Assessment Method); Scotland

INTRODUCTION

The Water Framework Directive (WFD) of the European Union (EU) came into force on 22 December 2000 and has, as its primary objective, the achievement of good surface water status within 15 years of that date (WFD, Article 4.1). Good surface water status is defined as, "the status achieved by a surface water body when both its ecological status and chemical status are at least 'good'" (WFD, Article 2; the five levels of ecological status are defined for natural water bodies as: high, good, moderate, poor and bad). Whilst the appraisal of biological data will be of prime importance, the WFD recognizes that for many water bodies, such data will be insufficient to make confident evaluations of ecological status. For water bodies of this category, provision is made for the use of hydromorphological and physico-chemical data so that indirect assessment of ecological status may be made with reference to those factors that are likely to affect the ecology (WFD, Annex V, 1.2.1). To attain good ecological status, aquatic systems must not significantly depart from reference (natural) conditions such that the values of the biological quality elements show low levels of distortion resulting from human activity. Thus, information describing hydrological regime, in particular the extent of the deviation from reference conditions, is likely to be of major importance for implementation of the WFD across the EU, since it is implicit that this may be responsible for less than good ecological status. As a response to this challenge, this paper provides a preliminary description of protocols developed on behalf of the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) for the assessment of the severity and extent of anthropogenic impacts on the hydrological regimes of Scotland's rivers. Lochs (lakes) were also considered within the method but will not be discussed further here. The method introduced in this paper is known as the Dundee Hydrological Regime Assessment Method (DHRAM). The DHRAM classifies the degree of alteration using a five-point scale. The remainder of the paper will discuss the details of this method.

DEVELOPMENT OF DHRAM

The physical and hydrological characteristics of rivers in Scotland, together with the ecology supported by them, are highly variable. Thus, complex relationships between hydrological alteration and ecology must be anticipated. It is therefore appropriate to consider the development of a method that assesses hydrological regime alteration on a broad basis. The first stage of development of what was to become known as DHRAM was an international literature review of the main consequences of hydrological regime alteration on ecology (Bragg *et al.*, 1999) which considered, *inter alia*, macrophytes, benthic biota, planktonic biota and fish.

In many countries, environmental management practices use ecological objectives as the basis for river flow regulation. Where research has indicated that a species or group within the aquatic community is impacted by human activity, the opportunity arises to specify river flow objectives to reduce the ecological impact to some "acceptable" level. The river flow objective may take the form of the requirement of a hydrological regime in which the timing of flows may be of significance for a certain species (e.g. Snelder *et al.*, 1998).

Gaps in the research

In many cases it can be inferred that ecological status may be regarded as "acceptable" so long as the flow objective is met and that other environmental pressures remain within acceptable limits. However, such flow objectives may be targeted on a single species or group, and may not necessarily satisfy the needs of other elements of the biota. Similarly, the simple provision of minimum acceptable flows presents problems in terms of the time distribution of flows necessary for some species and the determination of requirements for a complete functional ecology (Tennant, 1976). Many more complex models have been developed for the identification of the requisite river flows for an acceptable ecology, but it remains difficult to identify the extent of deviation from reference conditions that can occur before significant ecological damage results. Tools defining ecologically acceptable flow regimes require an understanding of hydro-ecological relationships, which are not widely available and were therefore not regarded as suitable for meeting the needs of assessing hydrological regime alteration in Scotland.

For the WFD, the threshold between "good" and "moderate" (on the Ecological Status Classification of high, good, moderate, poor and bad) represents the minimum ecological status required under any flow regime objective. It is therefore necessary to define good ecological status for water bodies across the EU for which biological data may be inadequate. It was clear that information on the extent of deviation from reference conditions, in relation to extreme flows and their timing, seasonal flows and flow variability, was needed.

The DHRAM approach

DHRAM was developed out of the work of Richter *et al.* (1996) of the US Nature Conservancy who introduced the Indicators of Hydrologic Alteration (IHA) methodology. The latter uses 32 indicators within five groups (Table 1) to describe hydrological regime and its deviation from reference conditions. Since the literature indicates that many different aspects of flow alteration affect species, the IHA methodology affords comprehensive focus on changes to hydrological regime. Where there is knowledge of the elements of the ecology that are particularly susceptible to hydrological change and the hydrological variables of greatest significance, management efforts can be directed to the present and future values of selected indicators only. Alternatively the IHA method can be used to gain an overall indication of the extent of hydrological change from reference conditions (Richter *et al.*, 1996). In each case, either the use of real hydrological data or the derivation of synthetic

Table 1 Indicators of Hydrologic Alteration (IHA) descriptors (Richter *et al.*, 1996) in five groups.

Group 1: Magnitude of monthly water conditions	**Group 2**: Magnitude and duration of annual extremes	**Group 3**: Timing of annual extremes	**Group 4**: Frequency and duration of high and low pulses	**Group 5**: Rate and frequency of change in conditions
Mean January flow	1-day minimum flow	Date of 1-day maximum flow	Mean annual number of high pulses	Mean flow increase
Mean February flow	1-day maximum flow			Mean flow decrease
Mean March flow	3-day minimum flow	Date of 1-day minimum flow	Mean annual number of low pulses	Number of flow reversals
Mean April flow	3-day maximum flow			
Mean May flow	7-day minimum flow		Mean duration of high pulses (days)	
Mean June flow	7-day maximum flow			
Mean July flow	30-day minimum flow		Mean duration of low pulses (days)	
Mean August flow	30-day maximum flow			
Mean September flow	90-day minimum flow			
Mean October flow	90-day maximum flow	**Group 3 dates are given as Julian days**	**High and low pulses are flows above Q_{25} and below Q_{75}**	
Mean November flow	Number of zero-flow days			
Mean December flow				

(estimated) data is required. Some overlap of results is to be anticipated: summer abstractions will, for example, impact both the monthly mean flows and the values of extreme low flow indictors (Puckridge *et al.*, 1998).

The Range of Variability (RVA) method, whereby the range of values of each indicator is found for pre-impact conditions along with a target range, was developed out of the IHA method (Richter *et al.*, 1997; 1998). In common with the latter, the RVA method is based on a comprehensive assessment of alterations to hydrological regime. However, the IHA method (Richter *et al.*, 1996) was the preferred basis for the development of DHRAM since the RVA method is highly sensitive to hydrological model error. The IHA method also permits the use of synthetic flow data (generated using *Micro Low Flows*, Natural Environment Research Council, 1996) for those sites where insufficient or no observed data exist. DHRAM applies the IHA method and makes the link with ecological impact through the concept of risk. In common with the IHA method, average alteration values are obtained for the five groups. These are used as the basis for generating a point score representing the severity of hydrological alteration, which, in turn, indicates the risk to ecological quality. Thus, DHRAM extends the IHA method (Black *et al.*, 2000).

Application of DHRAM to Scottish rivers

Application of the IHA method yields 10 average values; one change in mean (1a–5a) and one change in coefficient of variation (1b–5b) for each of the five groups (1–5; Tables 1 and 2). Each is based on an average of all the absolute percentage change values in the indicators within individual groups. Currently there is no ecological justification for assigning weightings to any of the group average values. Hence all 10 values (referred to as "summary indicators") are used to contribute equally towards the overall determination of extent of hydrological alteration.

To develop an empirical approach for this purpose, the IHA method was applied to 11 impacted rivers in Scotland, representative of all the major types of flow modification (hydroelectric and supply reservoirs; agricultural, industrial, fish farm and hydro flow diversion; effluent discharges). Land-use changes were excluded.

Table 2 Hydrological change thresholds used for the allocation of impact points.

IHA summary indicator	Percentage change in IHA group score:		
	Lower threshold (1 impact point)	Intermediate threshold (2 impact points)	Upper threshold (3 impact points)
1a (Group 1 mean)	19.9	43.7	67.5
1b (Group 1 CV)	29.4	97.6	165.7
2a (Group 2 mean)	42.9	88.2	133.4
2b (Group 2 CV)	84.5	122.7	160.8
3a (Group 3 mean)	7.0	21.2	35.5
3b (Group 3 CV)	33.4	50.3	67.3
4a (Group 4 mean)	36.4	65.1	93.8
4b (Group 4 CV)	30.5	76.1	121.6
5a (Group 5 mean)	46.0	82.7	119.4
5b (Group 5 CV)	49.1	79.9	110.6

Table 3 Definition of final DHRAM classes.

Class	Points range	Description
1	0	Unimpacted condition
2	1–4	Low risk of impact
3	5–10	Moderate risk of impact
4	11–20	High risk of impact
5*	21–30	Severely impacted condition

Questionnaire responses

1. The classification is dropped (down the table) by one if sub-daily flow fluctuations are significant, i.e. answer to Question 1 is "yes" and/or
2. Provisionally dropped by one class if flow cessation occurs as a result of the anthropogenic process(es), i.e. the answer to Question 2 is "yes".

* Class 5 is the lowest classification that can be allocated.

Summary indicator values were obtained from each river, giving the range of values that could be anticipated. Each set of results was then ranked such that threshold values could be identified for the lower and upper tercile values. For each summary indicator, values exceeding the lower tercile were allocated one impact point, those exceeding the upper tercile were allocated two points, and those exceeding the maximum recorded value were allocated three points (Table 2). Points from the 10 IHA summary indicators are then summed to arrive at a total impact score, with a theoretical maximum of 30 points. Table 3 shows how the total scores awarded are then used, with questionnaire responses, to arrive at a final assessment of severity of impact on a 1–5 scale, compatible with the WFD Ecological Status Classification. The final stage of the procedure incorporates the responses (yes or no) to two questions, which were felt to be of special importance:

1. Do sub-daily flow variations exceed 25% of the 95-percentile flow?
2. Do the anthropogenic impact(s) cause flow cessation?

Review of the literature and discussions with river regulators has indicated that both of these factors may have substantial effects on the aquatic ecology. Inclusion of these assessments within the five Richter *et al.* (1996) groups risks insufficient emphasis being attached to them. In the case of Question 1, stranding would be expected to occur as a result of sudden reductions in flow (the 25% has been arrived at on the basis of expert judgement, pending specific calibration). The effects of flow cessation (Question 2) would also be expected to cause species mortality and threaten to cause loss of ecological quality and continuity in the long term. Example results of the method, spanning a range of impacts, are presented in Table 4.

DISCUSSION

The hydrological basis for the development of DHRAM is well established. However, the acquisition of appropriate existing biological data for calibration of the risk scale and thereafter for validation has proved problematic. This is the result of two factors. First, the requirement that the scale of hydrological regime alteration should operate independently of other classifications means that the effects on biota arising from chemical or hydromorphological modification of the natural state of the water body

Table 4 Illustrative DHRAM results from impacted Scottish catchments.

River	Summary indicator points:										Total points	DHRAM class	Impact type
	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b			
Leven	0	0	0	3	0	1	0	0	0	0	4	2	Lomond barrage
North Calder	0	1	3	3	1	0	0	3	3	1	15	4	Supply reservoir
Clyde	0	0	0	0	0	0	0	0	0	0	0	1	Distant public water supply reservoirs
South Calder	3	3	1	0	0	0	0	1	0	0	8	3	Industrial effluents and abstractions
Megget	0	0	1	0	0	1	3	0	1	2	8	3	Supply reservoir
Eas Gobhain	1	0	1	3	1	1	2	3	1	3	16	4	Compensation reservoir
Upper Tay	2	0	0	1	0	0	0	0	1	0	4	2	Net import via hydro-electric power stations
Farrar	1	1	1	1	0	1	1	1	2	1	10	4*	Hydroelectric power generation
Elliot	0	0	0	0	0	0	0	0	0	0	0	2†	Spray irrigation
Garry	3	1	3	2	3	3	1	1	1	3	21	5	Hydroelectric power intake
North Esk	0	0	0	0	0	0	0	0	0	0	0	1	Fish farm abstraction

* Class lowered by 1 due to sub-daily hydroelectric power generation impacts.

† Class lowered by 1 due to summer flow cessation.

must be eliminated from the field data. Secondly, the method chosen for assessment of flow regime modification considers variables that influence aquatic organisms not only directly but also indirectly, e.g. through river channel maintenance, as well as factors that are important for riparian communities. This approach is favoured because it takes into account the whole of the aquatic system. However, the resulting scale of hydrological modification (Table 3) can be only partially calibrated on the basis of the WFD biological quality elements, namely aquatic flora, fish and benthic invertebrate fauna. Some of the departure from natural conditions indicated by the hydrological data will exert its principal effects on ecology outside the strictly aquatic parts of the system, e.g. on flood plains. In view of the complexity of the communities influenced by the range of changes described using IHA methodology, calibration of the scale of hydrological modification has not been attempted in the USA.

On a UK-wide basis, government/agency monitoring programmes are targeted primarily on water quality agendas, employing semi-quantitative sampling of macroinvertebrates and calculation of biotic indices such as the "BMWP score" delivered by RIVPACS (River Invertebrate Prediction and Classification System; Armitage *et al.*, 1983; Wright *et al.*, 1998). BMWP indices derived from existing data collected by the Scottish Environment Protection Agency (SEPA) were found to be insensitive to flow regime alteration, thus prompting consideration of alternative methods, e.g. LIFE (Lotic-invertebrate Index for Flow Estimation; Extence *et al.*, 1999). For river invertebrates, the LIFE approach looks promising in some respects, but a conclusive test of its ability to indicate the effects of altered flow regimes is not possible due to the lack of data from comparable natural (control) reaches. Thus, the LIFE approach also requires further exploration in the context of calibration. In general, the results of the exploration of existing biological data in conjunction with hydrological impact classes were inconclusive. This arises largely because the various sampling programmes were designed for other purposes and are not entirely suitable for this problem. Though less widely available, greater insights into ecological quality are emerging from the monitoring of salmonids.

The need for ecological calibration is therefore clear. The approach proposed in the future is to compare the biota of "neighbour pairs" of water bodies whose physical attributes are as similar as possible in all relevant respects (altitude type, catchment area type, geological type) except in the degree of disturbance to their hydrological regimes. Ideally, each pair would include a totally undisturbed/natural reference water body, although this may not be achievable in practice. In addition, chemical/physico-chemical and hydromorphological elements must be matched. It is suggested that an effective way to achieve this using existing methodology would be to carry out river habitat surveys and chemical surveys. There is no conclusive evidence that any of the biological quality elements is more sensitive than others to changes in hydrological regime, so the status of all groups should, ideally, be assessed in the neighbour pair within a strategy that allows provision for assessment of seasonal effects.

Acknowledgements We gratefully acknowledge the financial support and guidance of SNIFFER and its Steering Group.

REFERENCES

Armitage, P. D., Moss, D., Wright, J. F. & Furse, M. T. (1983) The performance of a new biological water quality score system based on macroinvertebrates over a wide range of unpolluted running-water sites. *Wat. Res.* **17**, 333–347.

Black, A. R., Bragg, O. M., Duck, R. W., Jones, A. M., Rowan, J. S. & Werritty, A. (2000) *Anthropogenic Impacts upon the Hydrology of Rivers and Lochs: Phase I, A User Manual Introducing the Dundee Hydrological Regime Assessment Method.* Scotland and Northern Ireland Forum for Environmental Research Report SR (00) 01F, SNIFFER, Stirling, UK.

Bragg, O. M., Black, A. R. & Duck, R. W. (1999) *Anthropogenic Impacts on the Hydrology of Rivers and Lochs, Stage 1 Report: Literature Review and Proposed Methods.* Scotland and Northern Ireland Forum for Environmental Research Report WR 98(50) I1, SNIFFER, Stirling, UK.

Extence, C. A., Balbi, D. M. & Chadd, R. P. (1999) River flow indexing using British benthic macroinvertebrates: a framework for setting hydroecological objectives. *Regul. Rivers: Res. Manage.* **15**, 543–574.

Natural Environment Research Council (1996) *Micro Low Flows V2.1 Low Flow Estimation in Artificially Influenced Catchments: Technical Reference and User Guide.* NERC, Swindon, UK.

Puckridge, J. T., Sheldon, F., Walker, K. F. & Boulton, A. J. (1998) Flow variability and the ecology of large rivers. *Mar. Freshwat. Res.* **49**, 55–72.

Richter, B. D., Baumgartner, J. V., Braun, D. P. & Powell, J. (1998) A spatial assessment of hydrologic alteration within a river network. *Regul. Rivers: Res. Manage.* **14**, 329–340.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. (1996) A method for assessing hydrologic alteration within ecosystems. *Cons. Biol.* **10**, 1163–1174.

Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. P. (1997) How much water does a river need? *Freshwat. Biol.* **37**, 231–249.

Snelder, T. *et al.* (1998) *Flow Guidelines for Instream Values.* New Zealand Ministry for the Environment, Wellington.

Tennant, D. L. (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. In: *Proceedings of the Symposium and Speciality Conference on Instream Flow Needs II* (ed. by J. F. Orsborn & C. H. Allman), 224–234. American Fisheries Society, Bethesda, Maryland, USA.

Wright, J. F., Furse, M. T. & Moss, D. (1998) River classification using invertebrates: RIVPACS applications. *Aquat. Conserv.: Mar. Freshwat. Ecosyst.* **8**, 617–631.