Long-term Consequences of Upstream Impoundment

by

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INTRODUCTION

Planners are becoming increasingly concerned with the maintenance or enhancement of the amenities of landscape, and their concern extends to the nature of stream systems because this affects the level of amenity as well as the potential for recreation. Far too often, proposed developments are evaluated on structural or architectural grounds, with little or no regard for the geomorphic, ecological, and aesthetic, harmony of the result. Environmental problems today have often resulted from short-term planning procedures, adopted because of technological, economic, or merely political, demand. Spontaneous decisions induced by short-term incentives are, however, characteristically responsive rather than anticipatory. Furthermore, a long-range planning approach is commonly rejected or ignored because of the constraints of uncertainty which lie between the present and the future.

In environmental management, decisions are most often made in a context in which the outcome is in doubt and the consequences of a given choice cannot be fully predicted. The costs and benefits of alternative actions are rarely absolute, and are frequently impossible to state in monetary terms. Nevertheless, can a failure to predict precisely the environmental costs of human activity provide a justification to ignore the probable or possible consequences?

Uniquely *Homo sapiens* has the power to change the environment very widely. More significantly, Man possesses two particular abilities: (1) to make rational decisions, and not simply spontaneous ones, and (2) to evaluate the various alternatives in order to maximize the potential of the environment, both in terms of resource development and the maintenance of environmental stability. The impartial application of these abilities would induce an anticipatory approach towards environmental problems, so that the full range of potential impacts would be considered during the planning phase.

The aim of environmental management should be to optimize development and resource-use by minimizing both costs and impacts (Clark, 1978). However, for this goal to be achieved, three developments are required: (1) an improved knowledge of the mechanisms of environmental response to human activity, (2) an improved awareness of the complex interrelationships between components within environmental systems, and (3) an improved perspective of time. This paper seeks to provide evidence for the need to adopt a long-term perspective in environmental management by due reference to the effects of reservoirs upon river systems in Britain.

The effect of Man's activities upon the environment may be viewed in terms of three orders of impact (Fig. 1). A first-order impact is the effect of an activity upon environmental processes ('Process alteration' in the figure), and will occur simultaneously with the activity. Second-order impacts are the changes of form, either geomorphological or ecological ('Channel changes' and 'Invertebrate population changes' in Fig. 1), which result from process alteration and become modified by constraints within the system. These impacts may require a time-period of between one and one-hundred years, or more, to achieve a new 'equilibrium' state. The third-order impact will reflect the feedback effects of the morphological changes upon the ecology, or *vice versa,* and will occur with a considerable time-lag in relation to the first-order changes of process: they are exemplified in Fig. 1 by 'Readjustment of invertebrate population' and 'Fish habitat'. Furthermore, it is the interaction of the different components of the ecosystem involved within the third-order time-scale that will have implications for the aesthetic and recreational potentials of rivers.

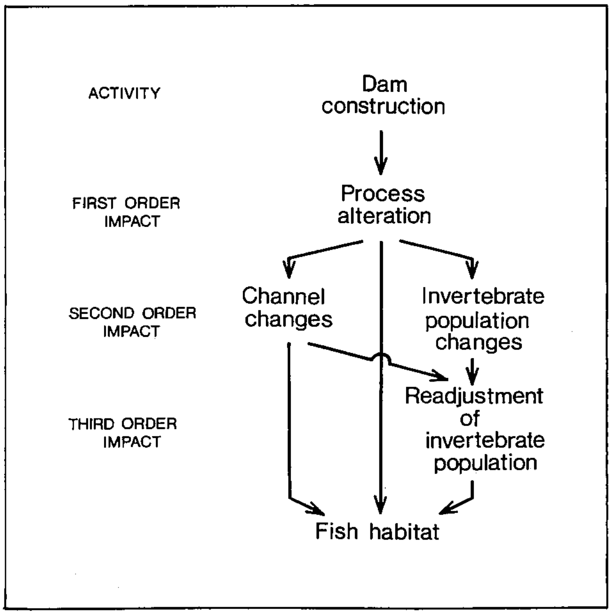

Fig. 1. *Orders of change within a river system after reservoir construction.*

Dams have been effectively employed for flow-regulation for over 5,000 years. In Western Europe, dams were not common until the late Middle Ages (Beckinsale, 1972), but since 1950 the number of dams has proliferated, and today 15.1% of river runoff is regulated (Lvovitch, 1973). Although the peak of dam-building activity may now have passed, the tendency is for fewer but larger dams (Beaumont, 1978). As reservoirs become more numerous and competition for water becomes ever-greater, the alteration of drainage-basin processes, and the consequent river-channel changes, will become increasingly significant. However, there may still exist a wider acceptance of the process changes than of the often less-readily-recognizable changes of form (Hirsch, 1977), or of the feedback effects upon local ecology. Indeed, process changes consequent upon human activity are well documented (e.g. Hollis, 1979), and so the emphasis here is placed upon the second-order impacts, and upon the implications of these for the third-order consequences.

FIRST-ORDER IMPACTS

River impoundment will effectively isolate sediment sources and alter the flow-régime for the channel below the dam. From a survey of the literature, Decoursey (1975) confirmed that significant reductions in peak rates of flow will occur as a consequence of reservoir construction. A 20% reduction has occurred in the magnitude of the 50-years' flood* for regulated central European rivers, and the mean annual flood along many impounded streams has been reduced by more than 25%. The attenuation of flood discharges by temporary storage above the spillweir crest of the dam will effectively reduce flood magnitudes below reservoirs having a surface area exceeding 2% of their catchment area (I.C.E., 1933). However, floods will also be absorbed, at least in part, within the reservoir volume if storage space is available. Thus floods on the Derbyshire Derwent, U.K., may now be virtually eliminated for even the most severe events by using, for flood protection, 20% of the storage in the Ladybower Reservoir (Richard & Wood, 1977).

Reservoirs having a large storage-capacity will trap in excess of 95% of the sediment load that is transported by the river (Leopold *et al.*, 1964): the bed-material load passing the reservoir will generally be nil, and suspended loads will have been reduced by some 65% (Nilsson, 1976). A testimony to the efficiency of reservoirs as sediment-traps is the decrease in the water-storage capacity of many reservoirs by over 1% per year (Buttling & Shaw, 1973). Thus, the sediment yields of the impounded Afon Rheidol, in mid-Wales, for two consecutive years were only 14% and 6%, respectively, of those of the neighbouring natural Afon Ystwyth (Grimshaw & Lewin, 1980).

The literature is replete with examples of induced erosion immediately below dams caused by the release of sediment-free water from the reservoir. Channel-bed-scour below dams, at rates of more than 15 cm per year (Leopold *et al.*, 1964), has caused considerable concern —in particular for the safety of structures within and alongside the channel. This concern is a reflection of the, as yet, indeterminate nature of channel changes in the short-term. For example, Buma & Day (1977) monitored channel-changes at eight locations over a five-years' period below a dam on Deer Creek, Ontario, following reservoir completion. Annual changes at a single location varied inconsistently, and considerable variations were observed between the locations during the five-years' period. Whilst half of the locations experienced net degradation (increase of bed-depth), at two sites there was an increase in channel-width by lateral erosion rather than an increase of depth by bed-scour. At the other four locations the cross-sectional dimensions were unchanged, although at two sites the channel had shifted laterally.

The processes operating within regulated river-channels will not simply reflect the changes of sediment loads alone, but will be the resultant of the interaction between the changed sediment-loads and the altered flow-régime. The elimination of flood events, for example, may effectively prevent channel-bed erosion. Indeed, the total sediment transport capacity of an impounded river to alter local configuration may be reduced by 75%, depending on the relative transport characteristics of the controlled releases and the normal flows (Bondurant & Livesey, 1973). Thus it is becoming increasingly apparent that induced erosion below dams may not be as problematical, nor yet as simple, as was previously thought, while the severity of the environmental problems arising from long-term sedimentation induced by flow-regulation are only now being appreciated.

Absolute equilibrium between the fluvial processes and channel form is seldom actually achieved, but river channels will adjust their morphology towards a steady-state condition in balance with the prevailing discharges and sediment loads. Consequent upon reservoir construction, the downstream patterns of erosion and alluvial sedimentation may become significantly altered, and major changes of channel morphology may be anticipated.

SECOND-ORDER IMPACTS

Studies of channel changes below dams have predominantly been concerned with the process of channel bed erosion induced by the storage of a river's sediment load within the reservoir. However, the examination of river-channel changes downstream from reservoirs in Britain (Petts, 1978) has revealed that a complex range of channel responses may be observed both in space and time. Fourteen rivers impounded for between five and eighty-five years, and involving reservoirs which regulate runoff from catchment areas ranging from 3.5 to 127 km^2, were studied. Changes of channel morphology were

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*The 50 years' flood is defined as the discharge which, from a sequence of annual maxima, recurs on average once every fifty years.

identified from intensive field-surveys, and the forms identified were placed in chronological sequence by reference to historical documents, maps, and the use of techniques of tree-ring counting and lichenometry. This information was supported by the utilization of empirical techniques describing the systematic variation of channel-form parameters established by Leopold & Maddock (1953).

Major changes have been observed, for example, downstream from Camps Reservoir in Scotland, fifty years after construction (Fig. 2). Channel changes have been identified by comparing the channel dimensions of Camps Water at specified sites, located by reference to the drainage area of each site, with the natural channel dimensions at the same location on neighbouring rivers. Comparison of the two data sets clearly illustrates the magnitude of channel change induced by upstream impoundment. Immediately below the dam, channel erosion has increased the cross-sectional area at bankfull stage (channel capacity) to twice that expected. However, channel capacities decrease rapidly downstream, so that within 250 metres of the dam the channel capacity has been reduced by 50%. At this location the channel is highly sinuous and is actively migrating across the floodplain.

During migration of the channel, the redistribution of floodplain deposits within the meander system has facilitated a relatively rapid adjustment of channel form, which has been achieved primarily by a reduction of channel width. The channel pattern becomes increasingly stable downstream, the rate of adjustment is reduced, and channel capacities return to the values expected (indicated by the line of equivalence on Fig. 2). However, this trend is interrupted by the injection of sediment at a tributary confluence. The coarser fractions of the sediment load have been deposited within the mainstream, so reducing the channel depth that a channel of reduced capacity is maintained for a short distance downstream.

Although the dominant adjustment has been a reduction of channel capacity, major variations exist if reference is made to channel shape. Furthermore, the description of channel changes below a variety of British reservoirs (Petts, 1979) has revealed a complexity of adjustments as existing both along individual rivers and between regulated channels. Nevertheless, classification of the observed changes has enabled the establishment of characteristic process–form associations and the recognition of four potential adjustments.

Potential Adjustments of Channel Morphology Below Dams

Immediately downstream from a dam, one of four potential adjustments will occur (Fig. 3), each reflecting a particular water-discharge–sediment-load interaction. However, in most cases no source of sediment is available, and so processes induced by sediment abstraction will dominate and channel degradation (bed-erosion) will occur. Erosional processes would increase the channel cross-sectional area preferentially by an increase in depth. However, channel-scour within a reach

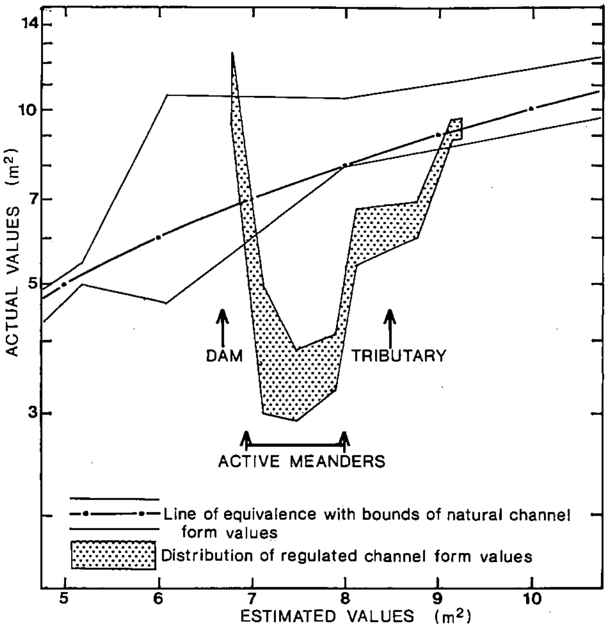

Fig. 2. *Changes of channel capacity downstream from Camps Reservoir, Scotland. The 'estimated values' were determined from a regression analysis of channel form data against drainage area for three neighbouring rivers.*

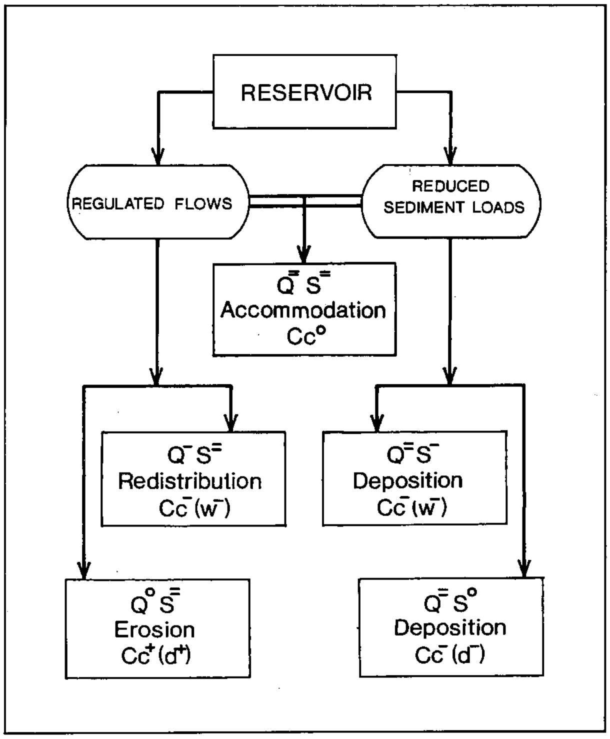

Fig. 3. *Potential adjustments of channel morphology to head-water impoundment. Flood magnitudes* - Q, *sediment loads* - S, *channel capacity (*w × d*)* - Cc, *channel width* - w, *channel mean depth* - d, ° *= no change, minus = minor reduction, double minus = major reduction, plus = increase.*

immediately below a dam would provide sediment for the next reach downstream, where deposition of the coarser fractions of the sediment load on the channel sides, together with induced lateral migration and the differential erosion and redistribution of floodplain deposits, may produce a channel of reduced cross-sectional area, achieved primarily by a reduction of channel width.

The injection of sediment by tributaries may markedly alter the balance between the regulated flows and altered sediment-loads within the main channel. Suspended sediments would be deposited if the sediment transport capacity of the mainstream flows had been markedly reduced, or if vegetation had encroached into the regulated channel. Deposition of the more mobile fractions of the bed-material load as channel-side berms would reduce channel width, and the coarsest material (which cannot be transported by the regulated mainstream flows) would be deposited at or immediately downstream from the confluence, reducing channel depth. Thus, degradation would be the dominant process of adjustment within reaches immediately below the dams, whereas farther downstream the differential erosion and redistribution of channel and floodplain sediments, and the introduction of sediment from tributary sources, would facilitate a response of channel morphology to the interaction of regulated flows and altered sediment-loads. Studies of British river channels subjected to headwater impoundment suggest that this response would be manifested by a reduction of channel cross-sectional area (cf. Petts, 1978, 1979).

In reality, a continuum of potential adjustments exist and the actual channel changes will reflect the existence of constraints within the channel system. These constraints include the resistance of the channel perimeter to erosion (such as the predominating particle-size of the bed materials, any bedrock outcrops, the degree of cohesion of the bank sediments, and the type and density of vegetation) which will affect any change of channel size and shape and also the rate and degree of lateral channel migration—and the existing channel dimensions (cross-sectional area and shape, as well as slope) which control the local variations in flow velocity. Nevertheless, within a long time-span, changes of channel morphology will occur downstream until the proportion of non-regulated runoff reduces the proportion of catchment impounded to less than 40% of the total area draining into the stream-channel.

Time-lags in Channel Response

Channel changes are associated with the initiation, originally, of erosional or depositional processes. The work done by a process, however, depends not only on the magnitude of the applied force, but also on the frequency of application (Wolman & Miller, 1960). If an erosional potential exists, the occurrence of any channel degradation will depend upon the frequency and intensity of competent discharges. Channels below many reservoirs in Britain are lined with coarse sediments, the banks are cohesive or well vegetated, and the regulated flows are below the threshold for sediment transport. In the absence of competent discharges, the river channel morphology will not change, and discharges will simply be accommodated within the existing channel form; then the only evidence of 'change' is likely to be a reduction in the frequency of over-bank flows. Similarly, channel aggradation will be dependent upon the frequency of sediment injection from upstream reaches or from tributary sources. The potential for channel change may exist but a rare, high-magnitude flood may be required to initiate adjustments. Thus, a considerable time-lag may exist between dam closure and the initiation of channel response.

The time-lag before channel response is initiated will vary both between regulated rivers and between reaches along a single channel. Downstream of large-surface-area water-storage reservoirs, or dams operated so as to maximize flood regulation, the time-lag may be markedly longer than below smaller reservoirs having a less significant effect upon the frequency of competent discharges. Furthermore, the frequency of competent discharges and of sediment injection will not be uniform throughout the length of the regulated river, but will vary both systematically and locally. Downstream of major flow-regulation reservoirs, the probability of channel response being initiated within a given time-period will increase with distance from the reservoir. This reflects the downstream increase in the frequency of competent discharges —a response to the input of non-regulated runoff.

Local variations may, however, be considerable. Thus deposition may occur at and below tributary confluences or downstream from a degrading reach, but major foci of deposition may be separated by reaches demonstrating no evidence of change. As an example, five years after the completion of Meldon Reservoir on Dartmoor, virtually no channel change had occurred immediately below the dam, whereas one kilometre downstream, below a major tributary supplying sediment, the deposition of channel-side berms and channel-bed aggradation had reduced the cross-sectional area to 53% of the natural dimensions. On a smaller scale, isolated channel changes may be induced by sediment transfer from a relatively wide to a narrower cross-section, or from sections of steep to shallower slope. Channel change may be initiated at one or more isolated sites located some distance downstream from the dam, and a considerable and highly variable time-lag may exist between dam closure and the initiation of channel response within individual reaches.

Complex Response

Environmental systems are, widely, capable of absorbing a stress caused by an isolated 'extreme' natural event. Studies of the effects of floods have demonstrated that a steady-state is maintained by a stabilizing response (Schumm & Lichty, 1963). However, many Man-induced stresses, and particularly those induced by reservoir construction, are sustained, and thus a new level of geomorphological activity is often induced. Graf (1977) demonstrated that the adjustment of many landforms to a Man-induced disturbance follows the negative exponential form of the rate-law used to describe the decay of radioactive isotopes. Thus after an initially rapid response, river channels will tend towards a condition of equilibrium at continuously decreasing rates of adjustment.

Repeated observations of river channel change, however, have revealed that the response appears to be 'stepped'. Thus observations of channel response in an experimental basin (Schumm, 1977) demonstrated that several alternating phases of erosion and deposition may occur as the channel system adjusts to the effects of change. For example, aggradation by deposition of sediment at a point on the main channel will reduce the energy-slope upstream, reducing the flow velocity and inducing further aggradation. However, over a period of time the depositional front will migrate downstream, the slope will steepen, and incision will occur. Thus, Wolman (1967) observed phases of aggradation and degradation of the channel bed below Fort Peck Dam on the Missouri River.

The alternation of erosional and depositional processes may result from the operation of three mechanisms: tributary rejuvenation, mainstream erosion during rare high-flows, and the operation of feedback effects within the main channel. A complex response within the mainstream may reflect adjustments throughout the stream network—particularly in response to fluctuations in the sediment supply injected from tributary sources (Fig. 4). The reduction in the magnitude and frequency of peak flows along the main-stream not only results in the deposition of tributary loads but also in the lowering of the effective base level of the tributary during times of flood, causing tributary rejuvenation. Rejuvenation will be manifested by channel bed erosion which migrates upstream until the channel slope is adjusted to the imposed base-level. During the period of slope readjustment, the supply of sediment to the main-stream may be markedly increased. Deposition within the main channel will modify the channel size, shape, and slope, so as to provide channel dimensions for the transmission of all the sediment supplied. However, occasional high mainstream discharges, depleted of sediment, may erode the deposits and enlarge the channel dimensions in the short term (Phase 1 in Fig. 4).

When once the tributary has adjusted its profile to the new base-level, the sediment supply to the mainstream will be reduced, and a phase of erosion may be induced within the main channel. Deepening of the main channel will effect a renewed period of tributary rejuvenation. This cycle will be repeated, but at progressively lower levels of intensity, until a state of balance is achieved between the regulated main-stream and the tributary (Phase 2 in Fig. 4).

Channel response involves the migration of zones of erosion and deposition which restore the system to equilibrium, so that erosional or depositional activity will not occur simultaneously throughout the length of the regulated channel. Changes of channel morphology at a single location will, however, affect the slope for the reach upstream, as well as the sediment supply to the channel downstream, and a complex sequence of interactions between the fluvial processes and channel morphology should be expected, with time, at individual locations. Along a regulated river the progressive redistribution of sediment, inter-adjustments between reaches, and interaction between the main river and tributary streams, will produce considerable variations in channel morphology within short time-scales. Over the long-term, the data derived from regulated rivers in Britain suggest that a uniform adjustment may be achieved, and that the dominant second-order impact will be a reduction in the cross-sectional area in response to the altered flow-régime.

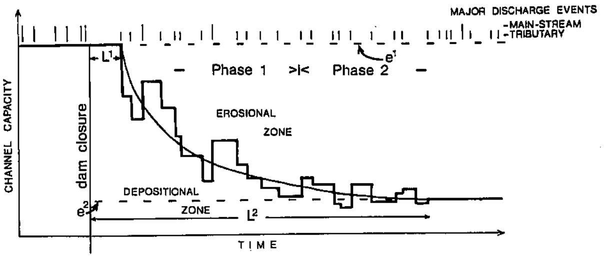

Fig. 4. *Complex response to upstream impoundment of a channel-reach located below a tributary confluence. Change from an initial equilibrium condition (*e^1*) to a new state (*e^2*) is characterized by two time-lags:* L^1, *the time between impoundment and the initiation of change (the reaction time), and* L^2, *the time required for attainment of a new equilibrium condition (the relaxation time). Note that during relaxation the variation of channel capacity will be complex and that the variations, which reflect the alternation of erosional and depositional activity, may be greater than suggested here.*

THIRD-ORDER IMPACTS

The alteration in magnitude and frequency of flood discharges, and the marked reduction in sediment load consequent upon reservoir construction, will have a direct influence upon the lotic fauna; but the long-term interaction of channel morphology and fluvial processes will also be significant. Changes in the hydraulic geometry, the variation of channel width, depth, and velocity, in space and in time, will affect the population of benthic organisms both quantitatively and qualitatively (Fraser, 1972). The particle-size distribution of the channel substrate, and the bed morphology, together control the quantity, velocity, and quality, of intra-substrate flows and the interchange between substrate-flow and stream-flow—factors that are all of importance in the determination of stream habitats (Vaux, 1968). Indeed, the form and composition of the substrate is well known to have an important influence on the distribution of benthic invertebrates (e.g. Minshall & Minshall, 1977), and channel sedimentation has induced a marked change in invertebrate populations (Saunders & Smith, 1962) and a loss of fish-food. Thus Boles (1980) found that the accumulation of fine sediments at riffles below Lewiston Dam operated as an adverse impact on both the fish-spawning and food-producing capabilities of Trinity River in northern California.

Geomorphological evidence from fourteen reservoired catchments throughout Britain has demonstrated that a complex sequence of channel adjustments will occur in both space and time. Changes in channel morphology will involve adjustments of the cross-sectional area and shape, bed slope and morphology, and substrate composition. Pools will become more or less filled with sediments and this will encourage the establishment of submerged and riparian aquatic vegetation of which the roots etc. will help to stabilize the surface.* The mean velocity and the distribution of velocity in space and time will change. Thus, the interaction of fluvial processes and channel morphology may be anticipated to induce readjustments in the populations of benthic invertebrates, Algae, and vascular plants.

Fish habitats are intimately associated with the hydrological, sedimentological, and morphological, characters of river channels, but the invertebrate population, as a source of food, is also important—environmentally, second only to the plants. Discharge alteration can directly affect the migration, spawning, and population composition and size, of fish species. However, changes in channel width and depth, channel bed form and sediment composition, as well as the population dynamics of the flora and fauna, are also very significant.

The diffusion of the effects of an applied stress, such as a dam and reservoir or artificial lake, throughout the stream system will be a slow process, and will be characterized by time-lags between the different components. The attainment of a state of equilibrium within the interaction between fluvial processes, channel morphology, and fish habitat, may occur only after a long time-period. An increasing number of ecological problems are being recognized in regulated rivers presenting very diverse environments (Ward & Stanford, 1979), but these are predominantly second-order impacts associated with the changes in discharge and water-quality. Although severe ecological problems have been observed as a result of channel changes induced at isolated locations by reservoir construction (Serr, 1972), the full nature of these third-order impacts may not be realized for some time to come.

CONCLUSION

During the last decade, international awareness and activity relating to environmental impacts has grown rapidly. This growth reflects both an improved scientific understanding of the potential problems and an intensification of public emotion. However, many decision-makers still expect the environment to respond in a simple, linear manner to an applied stress, and only perceive the immediate short-term consequences. Thus a considerable effort needs to be maintained in stimulating environmental awareness. Improvements in our understanding of how stressed environments may be expected to react will, of itself and alone, not ensure improvement in environmental management: a major gap will remain in the perception of decision-makers. This gap can best be rectified by widespread realization of the dynamic nature of the environment, and of the long time-period required for environmental readjustment in response to human impacts. A general awareness by the public must also be stimulated, because positive public participation in the decision-making process could assure the avoidance or modification of schemes induced by short-term economies or political gains.

Conceptual frameworks based upon a systems approach have become increasingly popular in recent years, but have perhaps had least impact upon those concerned with long-term environmental change. The environmental scientist should anticipate the consequences of human impacts over a fifty-, one-hundred -, or perhaps even five-hundred-years' time-scale, as well as those of immediate significance (Frye, 1971). Moreover, an interdisciplinary approach should be adopted within the long-term perspective.

Many of the environmental problems that have been identified during the past decade have arisen from a failure to appreciate the second- and third-order consequences of human activity over different time-spans. Results of theoretical and practical study of recent channel-changes, are so various that estimation of future changes which may be induced by human actions still remains widely problematical. Nevertheless, empirical relationships based upon intensive field-surveys may be applied to the assessment of historic changes and provide some basis for the prediction of changes in the future. The problem of erosion induced by clear-water releases from reservoirs has been recognized since the turn of the century, and has received considerable attention. However, an examination of channel changes downstream from reservoirs in Britain has revealed that channel degradation (deepening) may be localized in both space and time.

The dominant second-order impact within impounded British rivers has been a reduction of channel cross-sectional area. However, four primary morphological changes have been observed, namely, channel bed erosion increasing depth, channel width reduction achieved by the redistribution of the floodplain and channel boundary materials, deposition on the channel banks reducing width, and the reduction of channel depth by sediment deposition. Each of the changes reflects a particular association between the regulated flows, the changed sediment-load, the quantity and calibre of sediment injected, and the resistance of the channel-boundary materials to erosion. Channel response may occur only after a considerable time-lag with respect to dam closure. Adjustments will be initiated at one or more isolated sites, and changes may occur most rapidly some distance downstream from the dam. Furthermore, the adjustment will not follow a simple negative exponential decay-path but will oscillate about that path, reflecting alternate phases of erosion and deposition.

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*Aquatic vegetation in general and macrophytes in particular can act as an effective silt-trap that often helps to build up the surface on which they grow.—Ed.

Ecological changes will also be directly induced by discharge and sediment-load alterations. However, further adjustments will be effected by the different changes of channel morphology, so that a balance within the fluvial process–channel morphology–river ecology interaction, may only be observed within third-order time. Thus, the use of short-term observations immediately after dam construction for planning purposes may lead to serious management problems in the long-term.

In reality, river systems consist of numerous interrelated hydrological, sedimentological, morphological, and biological, components. The response of a river system to an applied stress will inevitably be complex, as the components have to adjust towards a new steady-state condition. Moreover, the response will be episodic and controlled by thresholds, so that a considerable time-period may elapse before any semblance of equilibrium is achieved. Thus it will only be with due appreciation of the intricate composition of natural systems and a realization of the delicate balance in which these systems are maintained, that the widespread present-day indifference towards a long-term perspective will be remedied and, hopefully, reversed.

ACKNOWLEDGEMENTS

I gratefully acknowledge the constructive suggestions made on an early draft of this paper by Mr M. Greenwood, and the advice generously offered by Professor K. J. Gregory throughout the research programme from which it stemmed in part and which had the support of an N.E.R.C. studentship.

SUMMARY

Since 1970 a large number of environmental problems have been identified as resulting from the long-term effects of human impacts. Consideration of human activity within the environment as three orders of impact, provides a basic framework for the appreciation and evaluation of long-term problems. Consequent upon dam construction, major changes of flood magnitude and frequency and of the quantity and calibre of sediment loads (first-order impacts), will induce the readjustment of channel morphology and ecology (second-order impacts). However, the macrophytic and macro-invertebrate population, for example, are also adjusted to channel morphology—particularly channel shape and substrate composition—so that further readjustments of the macrophyte and macro-invertebrate populations may be effected by changes of channel form (third-order impacts).

The interpretation of channel changes induced by headwater impoundment in Britain suggests that the readjustment of channel morphology, effected by process alteration, will be complex. Thresholds—particularly the resistance of channel-bed materials to erosion—will introduce time-lags into the pattern of response and of the migration of erosional and depositional activity within the main-stream. These, together with interadjustments between the main-stream and tributaries, will effect a complex sequence of alternating erosional and depositional phases of activity at individual locations within the main channel. Thus, a considerable time-period may elapse between dam construction and the attainment of any semblance of morphological, and consequently ecological, equilibrium. Furthermore, observations of the effects of river impoundment made at a single point in time, and particularly a short time after dam closure, may not reflect the long-term consequences.

The optimal use of a particular environment in terms of resource development, recreation, and amenity, requires action towards attaining geomorphic, ecological, and aesthetic, harmony of the results of development. However, two fundamental requirements are necessary for this, namely an improved attitude towards time (which requires a realistic consideration of the often slow rate of environmental response), and an improved awareness of the complex interrelationships which exist between the components of environmental systems—including their biota.

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A Step Towards Preventing Acid Precipitation?

Rain having a pH value of well under 7.0 is a phenomenon that is unfortunately now well known in large parts of Europe and North America. Sources of the chemicals causing this acidity of rainfall and snowfall are mainly industry and motor traffic with, in addition, the natural activity of volcanoes. Particularly notorious are the negative roles of sulphur dioxide and nitrogen dioxide in the atmosphere, and their reactions that lead to the final products of sulphuric acid and nitric acid. These acids, brought down in rain and snow, have highly unfavourable effects on the Earth's surface—particularly on aquatic (and to some extent on terrestrial) plant and animal life.

Besides sulphur and nitrogen dioxides (SO_2 and NO_2), the third most important product that is responsible for precipitational acidity is hydrogen chloride (HCl), the role of which is similar. Absorbed by atmospheric moisture, it then constitutes hydrochloric acid, which is no less harmful to the Biosphere and wildlife than are the other acids (H_2SO_4 and HNO_3). The HCl is emitted to the atmosphere locally in large amounts, often without any attempts at control: an important source of it may be the burning of heaps of rubbish in the open.

Each rubbish-heap is a motley collection of things which we humans do not need. A large proportion of the volume in such a collection is commonly occupied by plastic materials of various composition—including polyvinylchloride (PVC) which, on burning, yields the substances that are common to all plastics, namely H_2O, CO, CO_2, and smuts, but, in its case, also hydrogen chloride. The last has been used, together with acetylene (C_2H_2), to prepare vinylchloride ($CH_2{=}CH{\cdot}Cl$), that yields PVC on polymerization.

It is true that PVC is easily produced and suitable for cheap packaging and containers such as plastic bottles, bags, and cups. But as these are not 'returnable' and their lifetime of use is commonly very limited, yet they burn easily, it is necessary to replace the PVC by some suitable plastic material that is based on pure hydrocarbons, free from hydrogen chloride. Already as possible alternatives we have polythene, polyamide, polystyrene, polyacetate, polyacrylate, and a wide range of other organic compounds. The right one of them should be used for any 'short-living' packing and containers. The PVC remains suitable where there is need for resistance against corrosion, aggressive chemicals, or prolonged abrasion.

Until the plastic packaging and other applications of PVC can be widely recycled by some satisfactory means, the use of this plastic material should be limited strictly and considered carefully. We—both producers and consumers—should omit this substance from everyday usage, allowing its use in special cases only, when it will not be exposed to flames or high temperatures.

This recommendation has to be discussed internationally with other means of reducing the impact of acid precipitation in which the aggressive hydrogen chloride is commonly dissolved as an all-too-active ingredient. A rational effort by all of us might lead to a more healthy environment—in a less-damaged Biosphere—because we now know how to prevent this harmful phenomenon. The elimination of dangerous rain- and snow-acidity could be valuable evidence of international agreement that would notably strengthen global unity.

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