Geomorphic histories for river and catchment management

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River and catchment management usually proceeds from the identification of an undesirable state (e.g. pollution, sedimentation, excessive water extraction, dams, invasion by exotic species) to a strategy for reaching a desirable state described as a target. Desirable states are usually determined from community values, economic assessments and ecosystem functions, or a combination of these. Where a catchment is highly disturbed, the target is usually not a natural state, as that cannot be achieved while maintaining human uses, and a history is needed to document the disturbance, understand its cause and define the ‘existence space’, that is, the range of natural states that have occurred in the past. Where a catchment is less disturbed, a former natural state could provide a target for management. But which of the many natural (equilibrium) states that have occurred in the past should be the target? The paper reviews what is known of the quantitative difference between pre- and post-disturbance states, searches for the presence or otherwise of equilibrium and comments on the utility of this information for catchment management. The focus is on erosion and sediment transport.

Keywords: geomorphic histories; catchment management; erosion and sediment transport; sediment flux equilibrium

1. Introduction

There is now a body of literature that sets out the arguments for the use of history (including environmental history and palaeoenvironmental reconstructions) for various purposes in natural resource management, and river and catchment management in particular [1–7]. The authors of these and other works refer to the use of history to identify baselines or reference states as possible management targets. Recent advances in isotope geochemistry have enabled the calculation of erosion and sediment transport rates in catchments over millennia (see the study of Granger et al. [8] for the use of cosmogenic radionuclides) to at least 10⁶ year (see the study of Dosseto et al. [9,10] for a review of the use of the ²³⁸U decay series). Almost all authors in this field adopt the position that modern denudation rates should be compared with natural reference rates to quantify human impact. Some authors either claim or imply that the reference states could be targets for catchment management. There has been no examination of this body of

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One contribution of 10 to a Theme Issue ‘River history’.
research to explore the potential for use by catchment managers. In addition, many papers referred to here either imply or state that human activities have moved natural equilibrium systems to disequilibrium. The existence of a natural equilibrium state that could be a target for management, or the prospect of a future equilibrium state as the effects of human activities on catchment processes settle to new conditions [11], are both potentially attractive ideas for catchment management. A critical examination of the prospect of using equilibrium states for management does not appear to exist.

It is therefore the purpose of this paper to examine the various approaches for the identification of natural states as baselines for management targets from historical analyses, and to consider their utility, in the case of erosion and sediment transport. The existence of equilibrium is also examined and in so doing its utility explored. The focus on erosion and sediment transport comes about from the already mentioned recent developments in isotope geochemistry that allow new insights. Also, erosion and sediment transport is a worldwide catchment management problem.

Much of what appears here will seem to be basic knowledge (that is fundamental, or even esoteric, rather than applicable) of little or no relevance to managers. It may be so in its present guise because these ideas will need further development in specific management contexts. It is also the case that the distinction between basic and applicable knowledge is often slight, and, with thought, the basic can become the applied.

2. Perturbations, desirable states and history

The management of rivers and their catchments most often involves the identification and amelioration of perturbations from a desirable state. It can also be the maintenance of an existing desirable state that may be different from a pre-disturbance state. Perturbations can be changes of channel form (including degradation or aggradation of the bed, widening and/or, for example, conversion from a sinuous to a braided form), eutrophication, pollution by metals or organic compounds, invasion by organisms foreign to the area, changes in water temperature or pH, or disturbances to fish migration by the construction of weirs and dams.

Therefore, the desirable state may be an existing disturbed but acceptable one, a disturbed system that had a past natural condition or one close to a natural condition that can be defined or an undisturbed state that is therefore a natural one. The adjective ‘desirable’ may be that specified through community consultation and/or economic assessments, whereby human values are given priority, or it may be specified using concepts from ecology and geomorphology that define a healthy and functioning ecosystem, or it may be a hybrid. The term ‘disturbed’ is restricted here to those changes wrought by people rather than those brought about by major floods or climate change, for example. The adjective ‘natural’ is much harder to specify. It should of course be a state that precedes disturbance; but which state and how well are natural states known [12]?

The simplest desirable case is where disturbance has occurred and management will take the system back to a state that is acceptable but not natural. Examples of perturbations of this kind are pollution by compounds of human origin,
construction of dams, withdrawal of large amounts of water and eutrophication caused by inputs of sewage and/or fertilizer. The desirable states can be identified as pollution below an acceptable biological threshold, no or fewer dams, more water in the river and a non-eutrophic state, respectively, although the attainable states are likely to be dependent upon community values and needs, and cost.

The most difficult case is where the aim is to restore a river and its catchment to something resembling a natural state. When this aim is to be achieved for sediment transport rates, the problem is compounded. The challenge is to quantify the change to the erosion–sedimentation system from a natural to a perturbed state. Given that perturbations work their way through river catchments, often as waves (pulses or slugs) of sediment, the changes occur in time in different ways at different points in a catchment, raising the largely unresolved problem of travel times in rivers. Without a historical perspective, the analyst is left with the substitution of space for time, that is, using measured rates in a minimally disturbed catchment as a proxy for the undisturbed state of the catchment of interest. This approach assumes that all else is equal between the two catchments, an assumption that is very hard to test and unlikely to be viable where waves of sediment move along a river over decades to centuries. The historical data most often collected to reconstruct past sediment flows are the rates of sedimentation in sinks: a lake, a reservoir, a delta or the continental shelf [13]. While containing valuable records, these sinks do not provide coverage of the spatial complexity of catchments and they cannot by themselves resolve the travel times of sediment upstream of the sinks.

In addition, without a historical analysis, the manager may resort to flights of fancy, and construct a vision of a river that would be highly desirable from a human perspective but has not existed in nature. Historical analyses can, if sufficiently well resolved, define what we might call the ‘existence space’ for rivers and their catchments, that is, the range of system types that nature can produce and that the aims of people would be advised to stay within.

The arguments for historical analysis relevant to the documentation of perturbations and targets for management are therefore as follows: (i) perturbations occur through time and have different trajectories at different points along a river, and so they are historical; (ii) desirable states most often can only be identified from a pre-disturbance state and from history unless the analyst is convinced that the substitution of space for time is reliable; (iii) finally, history can provide the ‘existence space’ that management targets should stay within.

3. Equilibrium

The pre-disturbance state is sometimes equated with an equilibrium state (see e.g. Koppes & Montgomery [14], and the discussion by Trimble [15]), a reasonable simplifying assumption as a backdrop to further analysis of system behaviour in the view of Bracken & Wainwright [16]. An equilibrium state is also plausible given that physical systems tend to equilibrium as a balance between applied force and resistance, and because they contain negative feedbacks [17]. Unfortunately, geomorphologists have used the concept of equilibrium in many different and sometimes unhelpful ways. In this paper, the suggestion by Thorn & Welford
[18], following Ahnert [19], is adopted, namely that equilibrium refers to a mass budget concept. That is, the mass budget of an areal unit does not change over time because the output is equal to the input on average.

Thorn & Welford [18] prefer the term mass flux equilibrium because mass budget does not signify the existence of negative feedbacks to maintain the mean state around which small variations occur but cannot grow substantially. Nonetheless, the underlying meaning is the same, and to avoid adding to the equilibrium lexicon, the term equilibrium is used here in the sense of an unvarying (on average) mass budget. This use has the advantages of simplicity and geomorphic relevance, is directly relevant to the purposes of this paper, and harks back to the study of Gilbert [20] and his description of the adjustment of sediment transport rates downstream of an area in which erosion has been substantially increased. It might be expected that the time period over which equilibrium is either attained or maintained is dependent upon the time period examined [18], and that specific equilibria will differ between different geomorphic process–response systems [21].

If equilibria can be identified in pre-disturbance times, they could be useful targets for management because they would change within limited bounds, thereby avoiding community concerns, and their maintenance may be simplified because of negative feedbacks built into the system. However, this may be an unattainable wish that is nonetheless worth investigating. Before doing so, the different approaches to quantifying the differences between pre- and post-disturbance states are reviewed.

4. Pre- and post-disturbance states and perturbations

This section is organized according to the methods used to derive the histories of sediment loads and includes some discussion of equilibrium.

(a) Approaches from measured sediment loads and morpho-stratigraphy

From a large database of measured river sediment loads and the Area Relief Temperature (ART) model, Syvitski et al. [22] modelled the global pre-human sediment transport rate to the coast. The model is trained on a global database of measured sediment loads in either pristine rivers or from times before major human impacts. They calculated a global annual load of $14.03 \times 10^9$ $t \cdot yr^{-1}$. The calculated modern rate is $17.8 \times 10^9$ $t \cdot yr^{-1}$, assuming that reservoirs have not been constructed, or about 1.3 times the pre-human rate. The length of the pre-human period is not specified but should be relatively short given that the modelling depends upon data from modern undisturbed conditions that probably apply for about a thousand years. The modern rate cannot be used to calculate the sediment load reaching the global coast because about 26 per cent of the total sediment transport is trapped in reservoirs, small and large [22]. The modern transport rate to the coast is therefore $12.61 \times 10^9$ $t \cdot yr^{-1}$, which is 10 per cent smaller than the pre-human rate. Of course, these are global values, and spatial variability is large. The ratio of modern loads (removing the effect of reservoirs) to pre-human loads for 14 regions varies from 0.6 to 2. Values of the ratio less than one may be the result of errors in the estimates. The largest value of the ratio is in Indonesia, a major source of sediment to the world’s oceans and where
there are few large reservoirs to trap sediment. If the calculated pre-human loads are to be used as targets for management, or at least reference points or baselines against which to compare unmanaged and managed catchments, they should be used in individual catchments both within the regions defined by, and using the modelling tools developed by, Syvitski et al. [22].

By comparing time series of sediment loads in rivers in Asia for periods of up to 72 years, and taking account of soil conservation schemes, dams and sand mining in these rivers and their catchments, Walling [23] devised a simple model of what he called ‘temporal integration of human impact on the sediment load of an Asian river’. The conceptual basis of the model is the substitution of space for time, which is shared to some degree with the ART model referred to above. That is, the sediment load time series for different rivers are considered to be realizations of different stages of development of sediment loads in any river. The approach is in part substantiated by correlations between changes in the sediment loads and land use and conservation interventions. The model begins with an unchanging sediment load, called a baseline, before disturbance by land clearing and/or intensification of land use. The baseline can only be documented in detail where the causes of changes to the sediment loads are within the time period of the gauged record and therefore recent. Also, for the Huang He, a stratigraphically based estimate of the baseline is combined with the gauge record to provide a 6000 year time series. Disturbance of the baseline state increases river sediment loads to a point where management interventions occur and then begin to have an effect, thereby reducing sediment loads. Different rivers will of course be at different points in such a model.

While not wishing to over-interpret the model, as Walling makes it clear that it is simple, dams are thought to reduce sediment loads to below the baseline (a conclusion reached by Syvitski et al. [22]), whereas soil conservation, sediment control and sand mining may reduce loads to close to the baseline. The conceptual basis of this model needs further examination by stratigraphic analysis at the sites where it is not currently available, and by determining the major sources of sediment in each of the rivers to test the claimed causation of increased and decreased sediment loads.

Taking a different approach to the documentation of perturbations and pre-disturbance states, Dearing & Jones [13] (and also see the study of Montgomery [12] for more examples) have provided a compilation of sedimentation rates in a variety of sinks in both small and large catchments for periods up to 14000 years in many parts of the world. These authors conclude that, during the Holocene, human impacts have been greater than climate impacts as drivers of changes in sedimentation rates. Rates prior to major human disturbance have been used as reference values against which to estimate human impacts, rather like Walling’s baseline. The beginnings of human impact differ in age between sites, but nonetheless, when the ratio of the low rates (prior to disturbance) to the maximum sedimentation rate is plotted against catchment area, there is a clear nonlinear inverse relationship (figure 1). Small catchments are most sensitive to human impact, especially in mountains in low latitudes where impacts have been intense. Larger catchments are more buffered so that sedimentation rates and yields, as a result of disturbance, are much lower.

The various time series presented by Dearing & Jones [13] show that rates of sedimentation, and therefore sediment flows into the sinks, were in many
cases highly variable before human impact (also see [25]). The baseline was varied. This observation raises the question of which pre-disturbance state should be considered as the natural condition that might be used as a target for management, or at least a state to be aimed for even if not attainable. Furthermore, each study in this valuable collection required a lot of effort, involving variously statigraphy, chronometry, pollen analysis, magnetic analysis and geochemistry. It is likely that such studies will only be undertaken for applied purposes if the issues to be addressed are very serious, resources are considerable and there are suitable sediment sinks available. However, the summary of the data reproduced in figure 1 may have wide application without the need for fresh studies at locations of management interest, but only if the catchment of interest has characteristics similar to those in the data collection of Dearing & Jones [13]. The addition to figure 1 of sediment yields from small gullied catchments in Australia [24] raises doubts about the general applicability of the compilation. Updating figure 1 along with better process models coupled with palaeoenvironmental data may help to overcome this difficulty [5].

In the cases just discussed, the pre-disturbance sediment transport rate (or baseline) was lower than the post-disturbance rate. A different relationship occurs in the case of paraglacial erosion and sedimentation [26]. The perturbation is natural, induced by the retreat of glaciers and the release of large quantities of glacially derived sediment. The post-glacial rate of sediment transport falls after an initial pulse. The natural rate of sediment transport immediately following deglaciation is likely to have been higher than the modern rate, unless human disturbance has been particularly severe. Clearly, the state during deglaciation is neither a sensible management target nor an achievable one given that the
glaciers are either gone or much smaller. This may seem a trivial case given these comments, but it is included to illustrate the complexities of using natural states as management targets.

A far more interesting aspect of the paraglacial trajectory is that the sediment transport rate falls at different rates depending upon the catchment size [27]. The lower natural rate after the initial pulse following deglaciation, which could be used as a target for management, is therefore continually changing and at different rates depending upon spatial scale. Furthermore, the effect of the large sediment release can persist for up to $10^5$ years [28], so that human disturbances will be superimposed on a changing background for a very long time. Once again, what is the natural state? Also, the availability of large amounts of glacial debris in river valleys downstream of glaciated mountains means that the specific sediment yield rises as catchment area increases even in agricultural catchments, the reverse of the usual pattern in such landscapes [28]. These observations have several implications. First, managing agricultural land adjacent to such rivers to reduce sediment transport rates is likely to have little effect, an argument for a sediment budget as a guide to management. Second, rates of sedimentation in sinks of the kind discussed by Dearing & Jones [13] will reflect the paraglacial condition even in catchments where agriculture is important. Third, recovery from deglaciation will be slowed by other natural events such as rainfall-induced landslides or neoglaciation, confusing even more the analyst interested in identifying natural states.

(b) The sediment budget approach

A sediment budget is a quantitative account of the sources of sediment (inputs to a river or some other part of a catchment), the stores of sediment (also called stocks or accumulations) and the yield from the catchment (the output). Changes in the stores are the flows of sediment. Budgets can be calculated partially (e.g. sources only) and over many different periods of time.

Most sediment budgets document perturbations rather than pre-disturbance states, although some have achieved both [29]. Budgets also allow assessment of the degree to which a catchment is in equilibrium. In what follows, budget approaches are used to identify pre-disturbance states, document perturbations and assess equilibrium. The approach is not based on a review of all published sediment budgets, which is beyond the scope of this paper. Rather, global and sub-global assessments are used with some reference to highly resolved budgets in particular catchments.

If equilibrium exists in a catchment, in the sense defined earlier, then on average the input should equal the output of sediment on a time period set by the analyst for a particular purpose. For management, this time period should be long enough for negative feedbacks to reduce small perturbations close to the mean state. This period is not easily defined but is probably of the order of decades to centuries, depending on the size of both the catchment and the stores. At the catchment scale, equilibrium demands that deposition should be minimal, a state rarely seen in any but the smallest catchments. Therefore, it might be imagined that no large catchments are in equilibrium. This view is supported by the global analysis of Pinet & Souriau [30], who calculated the deposition rate in catchments of sizes ranging from $0.051$ to $5.908 \times 10^6 \text{ km}^2$ below a critical elevation $H_c$ of 600 m.
The relationship between deposition rate \((M_{\text{dep}}, 10^6 \text{ t yr}^{-1} A)\) and catchment area \((A, 10^6 \text{ km}^2)\) when forced through the origin is

\[ M_{\text{dep}} = 113.5 \pm 5.3 A, \quad p < 0.0001 \]

giving a value of \(M_{\text{dep}}\) of \(783 \times 10^6 \text{ t yr}^{-1}\) for the Amazon catchment \((A = 5.908 \times 10^6 \text{ km}^2)\) and \(2 \times 10^6 \text{ t yr}^{-1}\) for the Susitna catchment \((0.051 \times 10^6 \text{ km}^2)\) as examples. The systems are not in equilibrium.

A value of the Sediment Delivery Ratio (SDR; the fraction of total erosion that is transported out of a catchment) of 1 is therefore likely only over very long time periods when tectonic basins can fill and then empty, and travel times of sediment from uplands to the sea are shorter than the time period over which sediment transport is estimated. Panin [31] has calculated the SDR for various regions, including the globe, over periods of up to \(153 \times 10^6\) years. The global values lie between 63 and 77 per cent, the former for the Pliocene \((3.7 \times 10^6\) years in duration according to the time scale used by Panin) and the latter for the entire time period. The maximum SDR is 90–95 per cent for the European Alps, where there is little sediment storage. There is no relationship between the SDRs and the time period over which they are estimated, and the mean global SDR is 69 ± 4 per cent (means are shown with standard errors, when available, in this paper) over periods between \(153 \times 10^6\) and \(1.6 \times 10^6\) years. Although there are likely to be errors in the estimation of the masses of sedimentary rocks on land and in the oceans (and the partial destruction of these masses), the data source for this study, and some of the estimates come from large regions rather than the entire globe, it is clear that even over \(153 \times 10^6\) years equilibrium is not attained. This is not surprising given the formation of depositional basins. For example, an SDR of 83 per cent was reached in the catchment of the Meuse River in Europe after \(0.65 \times 10^6\) years because of sediment storage in the Roer Valley Rift System [32].

These deep time insights have been extended to the entire Phanerozoic (the last \(542 \times 10^6\) years) by Wilkinson [33] and Wilkinson & McElroy [34]. Wilkinson [33, p. 164] suggests that equilibrium has been ‘more or less’ attained globally over long time periods with a lower sediment transport rate than what occurs in the modern condition, which they imply is in disequilibrium. They show that there have been order-of-magnitude variations in the supply of sediment to global stores during different geological epochs because of uplift, subsidence and climate change. These observations suggest that equilibrium is unlikely even over the Phanerozoic, but these authors nonetheless calculate a mean global denudation rate of \(0.02 \pm 0.003 \text{ mm yr}^{-1}\) for the entire time period. They then compare this value with that derived from modern large river sediment loads by Syvitski et al. [22], concluding that human activities have increased sediment transport to the world oceans by a factor of about 4. The deep time denudation rate is therefore considered to be a pre-disturbance baseline.

A similar analysis has been performed for the large river catchments of Asia by Clift [35]. Using high-quality seismic records for continental margins offshore from the large rivers, and correcting for compaction and the biogenic fraction of the sediments, the clastic sediment yields for the last \(1.8 \times 10^6\) years were calculated. The ratio of modern loads to the long-term estimates varies from 1.2 for the Indus River to 16 for the Yangtze River, with a mean of 6.1 ± 2.1.
These comparisons of modern rates with very long-term denudation rates are however problematic for two reasons. First, Gardner et al. [36] showed that rates of erosion are dependent upon the time period over which they are measured because over long periods there are more times of erosion inactivity than during short periods. Using their scaling equation, the global denudation rate rises to $0.82 \pm 0.12\, \text{mm\,yr}^{-1}$ and the modern rate remains almost unchanged at approximately $0.14\, \text{mm\,yr}^{-1}$, an increase of about 6 between the long-term past and the present. Second, for the period considered by Panin [31], about 24 per cent of eroded rock and soil did not reach the ocean. For the last few decades, the time period over which most measurements have been made of soil erosion and sediment transport in rivers, the SDR is likely to have been much less than 10 per cent [37], the major exception to which is the Huang He, where the SDR is approximately 1 because of the extremely high transport efficiency of hyperconcentrated flows [38]. So, much more than 90 per cent of eroded material is stored on land in catchments. If it is assumed that approximately 24 per cent of eroded soil and rock will always be stored in catchments, that is, the long-term SDR is approximately 66 per cent and never reaches 100 per cent, then greater than 66 per cent of the products of modern erosion are yet to reach the global oceans. This amounts to $7.5 \times 10^9\, \text{t\,yr}^{-1}$ on average, based on the estimates of the flow of river sediment to the global oceans [22]. Therefore, the influence of land use is greater than that calculated by Wilkinson & McElroy [34].

The storage in catchments of more than 66 per cent of the products of modern erosion shows that the current condition is not at equilibrium, although from the work of Panin [31] it appears that it will never be. But the modern system is much further from equilibrium than during any of the geological periods considered so far, although this may be because the time periods over which the SDRs have been calculated over the last $153 \times 10^6$ years are orders of magnitude longer than the time periods for which modern SDRs have been estimated. During each of the geological periods there were perturbations that increased erosion and for a while decreased SDRs at river mouths. Glaciation and deglaciation are likely candidates, as seen in the discussion of the paraglacial phenomenon, along with other climate changes, sea-level changes and earthquakes. These variations cannot be detected in the averaged records used by Panin [31].

Given that sediment storage is the main manifestation of disequilibrium in both the modern era and geological time, some attention will now be paid to the nature of the storages. Wilkinson & McElroy [34] summarized information about the deposition of alluvium derived from the erosion of cropland in the USA. This post-settlement alluvium (PSA) is accumulating vertically at an average rate of about $13\, \text{mm\,yr}^{-1}$, in contrast with cropland denudation of about $0.6\, \text{mm\,yr}^{-1}$. The alluvium accumulates in less than 5 per cent of the cropland area. The existence of PSA has also been demonstrated in Australia [29] and is likely to occur in other parts of the world where settled agriculture is recent or in places where agriculture has ancient origins but has been extended into new areas recently. Where agricultural impacts are ancient, soil loss from hillslopes has resulted in considerable accumulations as colluvium and alluvium (see e.g. the study of Bell & Boardman [39] for Europe). For example, in England and Wales, up to 580 mm of hillslope soil has been eroded and up to 250 mm of this has been accumulated as alluvium in catchments less than $1\, \text{km}^2$ in area, an amount that decreases as catchment area increases [40].
Detailed sediment budgets in the USA allow for insights into the dynamics of catchments disturbed by clearing, grazing and cropping. The most interesting information from the viewpoint of equilibrium in erosion and sediment transport systems is that of Trimble [41,42]. He showed that, although sediment sources and quantities in the 360 km² Coon Creek catchment in Wisconsin have changed markedly over the last 140 years, the yield has changed little if at all. Sheet and rill erosion of hillslopes, gully erosion and erosion of tributary channels have all declined, from which it might be concluded that yield has declined. But alluvial storage has also declined and therefore a larger fraction of eroded material is leaving the catchment. The SDR in 1938–1975 was 15 per cent and between 1975 and 1993 it was 32 per cent. The inputs and the outputs for these two periods are clearly not equal, and they were not so for the earlier period 1853–1938 when the SDR was 9 per cent. That equilibrium does not exist in this and other similar post-disturbance catchments was argued forcefully decades ago by Trimble [15].

The other major sediment storage in the world’s catchments is in water supply reservoirs, as already discussed. Syvitski et al. [22] have shown that about 26 per cent of the global sediment in transit is trapped in reservoirs. Stores also occur in large floodplains that are not included in the PSA calculations, and in coastal deltas.

(c) Denudation rates using the $^{238}\text{U}$ decay series

The nuclides in the $^{238}\text{U}$ decay series in surface rocks and soils will be in secular equilibrium at or after $1\times10^6$ years. During chemical weathering and physical erosion, radioactive disequilibrium occurs in the decay chain as nuclides are partitioned between the water and sediment. A mass balance of the decay chain nuclides can be used to estimate the equilibrium between soil erosion and river sediment transport and also the residence time of particles in a river [43]. The equilibrium state, called steady state by those involved in these studies, is when the rates of soil production, soil erosion and sediment transport are the same. This is equivalent to the notion of equilibrium used here. The calculation of the river sediment transport rate, expressed as either specific sediment yield or denudation rate, is a theoretical concept because large climate changes during the last $1\times10^6$ years have occurred on time scales of $10^4$–$10^5$ years [44], making it unlikely that the transport rate has remained close to constant. Nonetheless, the equilibrium denudation rate has been compared with modern rates in an attempt to establish the state of degradation of modern soils [43].

Calculations of the equilibrium denudation rate are available for the Amazon, Murray-Darling, Mackenzie and Narmada catchments, and for two catchments in Iceland [9,10,45,46]. Additional less reliable estimates are available for the Congo, Mississippi and Fenland catchments [45,47–49]. If over $1\times10^6$ years, the catchment SDR = 1, then it might be expected that the equilibrium denudation rates would show variations with catchment area that are less than those of modern rates. However, this is unlikely given the conclusions reached earlier about long-term SDRs. There is also another reason to investigate the spatial pattern of these denudation rates: comparison with previous analyses of the spatial patterns of modern denudation rates to identify natural and disturbed patterns [50,51].

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Calculated specific sediment yields for the Amazon and four sub-catchments in the Murray-Darling show rapidly declining trends with catchment area (figure 2), like those seen in modern sediment yield data from agricultural catchments [51]. There is some slight evidence that yields remain approximately constant in larger catchments in both cases. Of course, the number of available data points is not sufficient to be certain about this tentative conclusion. Insufficient data exist in other catchments to draw even tentative conclusions.

More data exist from a wide range of catchment sizes for the comparison of modern rates with equilibrium rates. Most values are greater than 1, some close to 1 and some less than 1. The average value for those greater than 1 is 6.3 ± 1.8 (n = 13) and for values less than 1, it is 0.3 ± 0.1 (n = 9). The positive values come from the Amazon, Narmada, Murray-Darling and the Jökulsá a Fjöllum in Iceland. Values greater than 1 are found in the Mackenzie and Hvítá-S in Iceland.

In the Amazon, a strong relationship is found with a rapidly declining ratio modern/equilibrium from the Andes (figure 3). Modern rates are much higher in the mountains than they would have been under equilibrium conditions, even though equilibrium rates are very high in the mountains (figure 2). Given the short calculated sediment residence times in the upper Amazon catchment, Dosseto et al. [9] explain the high values of the ratio by increased precipitation within the last 5 × 10^3 years.
Figure 3. The ratio of modern to equilibrium sediment yields as a function of catchment area for the (a) Amazon and (b) Mackenzie catchments from data in Vigier et al. [45] and Dosseto et al. [9]. The equilibrium values are based on the $^{238}\text{U}$ decay series.

The Mackenzie catchment is included in figure 3 as a contrast to the Amazon. All values of the ratio in the Mackenzie are less than 1, showing that the modern denudation rate is less than the equilibrium rate. In this case, Vigier et al. [45] suggest that the dominant erosion process in this catchment is glaciation, which is much more efficient than the fluvial erosion that dominates modern denudation rates. This view is also that of Church & Ryder [26]. More recent work by Koppes & Montgomery [14], however, shows that erosion by glaciers has been overestimated by up to three orders of magnitude in modern records of sediment discharge because they represent the deglacial pulse rather than a long-term rate. Another explanation is that offered by Kirchner et al. [52] who also found values of the ratio less than 1 in the Idaho Mountains using $^{10}\text{Be}$ to calculate denudation rates (see below). They argue that the modern sediment load estimates do not include sufficient large floods to be representative of the average condition.

This conclusion may be given more weight when both modern and equilibrium denudation rates are rescaled using the method of Gardner et al. [36], adopting a time period of $10^{6}$ years over which the equilibrium rates are determined. Out of 21 reliable estimates of the equilibrium rate worldwide, only four ratios of the two rates are greater than 1 in the rescaled data. The values of the ratio less than 1 have a mean of $0.21 \pm 0.05$ and that greater than 1 is $1.88 \pm 0.38$. The average uncertainty for the modern rates is likely to be about 40 per cent, while, for the equilibrium rates, it is likely to be about 10 per cent, which in combination is insufficient to explain the differences between the two rates when the ratio is either greater than or less than 1.

However, these rescaled values need to be treated carefully. Gardner et al. [36] showed that the slope of the regression equation that relates the depth of erosion (rather than rate and called distance by these authors) to the time interval over which the distance is measured has a slope less than 1. As seen earlier, this observation was interpreted to be the outcome of more periods of erosional inactivity over long time periods. But some of the differences in rates over various time periods are likely to have been affected by mountain building in tectonically active areas. Until this alternative hypothesis can be tested, the unscaled values
are adopted. That is, the ratio values less than 1 are the result of underestimation of modern denudation rates, and the real ratios will therefore be higher than the value of 6.3 and higher than the value of 0.3. The values greater than 6.3 show that modern rates are not at equilibrium but the extent to which the values greater than 0.3 are not at equilibrium is uncertain. For the mean value of 0.3 to be equal to unity, the modern rates would need to have been underestimated by factors between 2 and 12 in the case of the Mackenzie catchment. While the lower factor is plausible, the higher seems to be unlikely; although it will be shown later that a difference of 18-fold in the Idaho Mountains is best explained by underestimation of modern loads. It seems that some catchments have modern rates of denudation lower than equilibrium rates and, for these, underestimation of modern loads and, in some cases, long-term glaciation producing more sediment than fluvial processes are the most likely explanations.

(d) Denudation rates from cosmogenic radionuclides

Spatially averaged catchment denudation rates can be calculated using measurements of $^{10}$Be in the quartz fraction of river sediments [8]. As in other measurements of long-term denudation, the authors of papers who use the $^{10}$Be technique argue for baseline estimates against which to compare modern rates disturbed by human activities [52–54], although the applied use of the baselines is not explained. The duration of the baselines varies widely, however, because the period over which the denudation rates are calculated is the time it takes to erode 60 cm of regolith. Therefore, where erosion is high, the period can be just a few centuries, and where erosion is slow, the period can be up to $10^3 \times 10^3$ years. The denudation rates so calculated are not claimed to be in equilibrium with formative conditions, but are averages over periods long enough to avoid the problems of short-term measured loads of the kind discussed earlier.

The samples used for analysis of cosmogenic nuclides come from both tributary and trunk streams. Comparison between point determinations of long-term denudation rates and modern rates is pursued below. In addition, the spatial patterns of denudation rates are examined to enable comparison with spatial patterns of modern rates, which appear to differ between disturbed and undisturbed catchments [50,51].

Results from a variety of geomorphic settings are provided in figure 4. A compilation of data from European rivers by Schaller et al. [55] is shown against catchment area, revealing high variability in catchments with areas of up to about $25 \times 10^3$ km$^2$. Three estimates in larger catchments show much less variability. This spatial pattern is similar to that shown in figures 2 and 3, suggesting that the equilibrium values based on $^{238}$U series are not unrealistic, even though they are theoretical states; or perhaps this is coincidence. When separated by catchment, more information is obtained (figure 5). High variability occurs in areas at less than $10^3$ km$^2$ in the Regen catchment, settling to near-constant values at the catchment mouth at 2911 km$^2$. There is no relationship in the Neckar catchment, and the samples near its mouth (at 14 447 km$^2$) include material from many different sources that had different denudation rates, suggesting that this river is not dominated in its downstream reaches by one source such as the channel or nearby hillslopes. Denudation rate steadily increases with catchment area but there are no data from areas less than 900 km$^2$, where high variability might be.
Figure 4. Denudation rates based on $^{10}$Be as a function of catchment area in (a) middle Europe (from data in Schaller et al. [55]), (b) the Ecuadorian Andes (from data in Vanacker et al. [54]) and (c) the Idaho Mountains (from data in Kirchner et al. [52]).

expected. Finally, the pattern in the Loire/Allier catchment is similar to that in the Regen, with high variability in areas less than $15 \times 10^3$ km$^2$ and then near-constant values to $42,637$ km$^2$.

Because the denudation rates vary so much in the four European catchments, and elsewhere, the time periods over which these rates are calculated (the so-called apparent age) also vary. The ranges of the apparent ages are: Loire/Allier 8.3–101.6 kyr; Meuse 10.7–42.1 kyr; Neckar 5.7–14.1 kyr; Regen 19.9–31 kyr. The calculated denudation rates for each sampling point are therefore averages over different time periods during which different climates and presumably denudation rates have prevailed. Their comparison spatially and between catchments may not be valid as an indicator of controlling factors, and therefore their comparison with modern rates is made more difficult. However, where the mean apparent ages are similar, then comparisons between catchments are facilitated. The means in the Regen (24.5 ± 0.8 kyr), the Meuse (24.4 ± 3.1 kyr) and the Loire/Allier (23.2 ± 3.0 kyr) are the same and therefore can be compared. The mean for the Neckar is 8.2 ± 0.7 kyr and therefore integrates only Holocene environments that affect erosion rather than glacial, deglacial and Holocene environments as is the case in the other three catchments. Similarly, when the standard errors of the mean apparent ages are small for a single catchment, comparisons between sub-catchments are possible. This is the case in the Regen and the Neckar, but, for these reasons, the conclusions reached about the spatial patterns in the Loire/Allier and Meuse are less reliable than those for the other two catchments.

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Figure 5. Denudation rates based on $^{10}$Be for (a) Regen, (b) Neckar, (c) Meuse and (d) Loire/Allier catchments in middle Europe based on data in Schaller et al. [55].

The spatial pattern in the data from the Ecuadorian Andes [54] is like that in the aggregate data from Europe but in a much smaller range of catchment sizes (figure 4). In the Idaho Mountains, there is high variability in catchments less than 10 km$^2$ in area, then a rising trend to areas of about 35 × 10$^3$ km$^2$ (figure 4) [52]. The range of apparent ages is small and so the problem identified above is not severe.

Comparisons of the long-term denudation rates with modern rates are provided for two areas in figure 6. In the Idaho Mountains, as noted earlier, the ratio is less than 1. Kirchner et al. [52] suggest that this is because of underestimation of modern loads. Only five of the 30 studied catchments have been glaciated, thereby ruling this out as a general explanation of the difference. Part of the area has been subjected to timber harvesting, which would be expected to increase modern loads, making the 18-fold difference between the two sets of estimates even harder to explain. Underestimation of the modern loads by a factor of 18 suggests that very large events have not been captured during the period of monitoring, which has been up to 84 years. A similar argument is advanced to explain a ratio of 0.25 in the Blue Mountains in Australia [56], invoking infrequent mass movements and large floods not captured by monitoring.

In the Ecuadorian Andes, the spatial pattern of the ratio is markedly different from that in the Idaho Mountains, showing a strong inverse relationship, with all values greater than 1 (figure 6). This pattern is the same as that in figure 3 for the entire Amazon catchment using $^{238}$U series, where the high values in the
mountains were explained as the result of a Holocene climate change. For the results based on $^{10}$Be, this is an unlikely explanation because the time period over which the denudation rates in the mountains have been estimated is too short. An explanation is not forthcoming at this time.

In the southern Appalachian Mountains, a range that is tectonically inactive and maintained isostatically, $^{10}$Be measurements show spatially homogeneous sediment production across different rock types from the present to $10^5$ years at least [57]. While providing evidence for equilibrium, because rates have not changed over long periods, suggesting that inputs and outputs are equivalent, the possibility exists that the modern rates have been underestimated as elsewhere.

In the tropics, Brown et al. [58] estimated both long-term and modern denudation rates in an undisturbed 3.26 km$^2$ catchment in Puerto Rico and found that, even though the ratio between the estimates is approximately 1.7, the uncertainties indicate that they are not different. Also in Puerto Rico, Brown et al. [53] show without equivocation that modern denudation is higher than the pre-agricultural rate by a factor of 2. Hewawasam et al. [59] reported modern rates of denudation 10–100 times the natural rates determined by $^{10}$Be in small catchments in Sri Lanka.

From the data referred to in this paper, the mean ratio of modern to long-term (based on $^{10}$Be) denudation rates in medium size and large catchments (>15 000 km$^2$) is $14.95 \pm 2.39$ for those cases where the ratio is greater than 1. This is the highest of all the aggregate estimates and may be because all of the data come from medium size catchments that are smaller than those from which $^{10}$Be data come, for example. Sediment yields tend to be higher in smaller catchments (figures 3 and 4).

5. Discussion and concluding remarks

Having surveyed much of the available data, the relevance of these data and findings will now be examined in relation to the purposes of this paper.

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(a) Quantifying the difference between pre- and post-disturbance denudation rates, and their spatial patterns, and their utility for catchment management

Global modern post-disturbance denudation rates are higher than global pre-disturbance denudation rates, calculated over time periods stretching over $542 \times 10^6$ years, by factors between 1 and 6. This does not include the $^{10}$Be-based estimates because they mostly come from medium size catchments. The range includes the pre- to post-human rates without reservoirs [22], the increases for catchments between $10^4$ and $2 \times 10^6$ km$^2$ [13], the unscaled data from Wilkinson & McElroy [34] and the ratio of modern/long-term denudation rates based on $^{238}$U where the ratio is greater than 1. There are only four estimates available but the factor increase is approximately related to the time period over which the estimate has been made. That is, the lowest factor of about 1 relates to about a millennium and the highest factor is from the longest record. This is not consistent with the findings of Gardner et al. [36], where rates of erosion lessen as the time period over which they are estimated lengthens. The trend cannot be explained at the moment.

The relatively narrow range of factors of increase between 1 and 6 suggests that there are stabilizing forces that reduce the amount of increase that is possible as a result of human activities. The obvious stabilizing phenomena are channel aggradation, and deposition on floodplains and, recently, in reservoirs. Given the relative size of floodplains and channels, it is likely that the former are more significant buffers. That floodplains are major buffers of sediment transport has recently been challenged by Clift [35] in the case of Asian rivers. His data show that the ratio of modern to long-term denudation rates averages $6.1 \pm 2.1$. This does not rule out a role for floodplains as buffers, recalling that Clift was responding to a rather extreme result by Métivier & Gaudemer [60] that suggested that floodplain buffering effectively stopped any of the products of enhanced erosion reaching the oceans in Asia.

It would be speculation to estimate the likely effect of the $7.5 \times 10^9$ t yr$^{-1}$ of sediment released by human activities that has yet to reach the world’s oceans without a reliable model of sediment travel times that takes account of channel and floodplain change as a result of increased sediment loads, the filling of reservoirs with sediment and the removal of reservoirs in some countries. Observations by this author in Indonesia and Timor Leste, where there are few large reservoirs and high erosion rates, show that increased erosion rates as a result of land use, particularly in the uplands, are aggrading the rivers, which are widening and thereby eroding their floodplains, producing more sediment. It is not known if the addition of sediment from the floodplains is greater than the rate of aggradation and thereby increasing the sediment load at the coast. Understanding and quantifying these relationships is the awaiting challenge.

Spatial patterns of denudation rates are believed to differ between modern disturbed and modern undisturbed catchments. Dedkov & Mozsherin [50] found two primary relationships between specific sediment yield (SSY) and catchment area ($A$). The first is an inverse relationship in cultivated catchments, where most sediment is said to come from the land surface. The second is a positive relationship in undisturbed forested catchments, where most sediment is said to come from in-channel erosion. Vente et al. [51] confirmed these two patterns, and found a third, as follows: (i) low SSY rise with $A$ and then fall, equivalent to the
first primary pattern of Dedkov & Mozsherin [50]; (ii) steadily rising values of SSY with $A$ until there is a small fall at very large values of $A$, equivalent to the second primary pattern of Dedkov & Mozsherin; and (iii) values of SSY rise with $A$ then stabilize with some large variations around the trend as a result of spatial variations of soil erodibility, topography and land use, a variant on the second primary pattern.

The second primary pattern of Dedkov & Mozsherin [50] may be considered as an equilibrium state in undisturbed forested catchments in high latitudes, but is based on a small number of examples with only a few decades of sediment load measurements. If the spatial patterns of long-term denudation rates derived from isotopic analyses were similar to the modern examples, then more confidence could be placed in the idea of equilibrium. Only the catchments from the Idaho Mountains and middle Europe (figures 4 and 5) have environments similar to those catchments used by Dedkov & Mozsherin [50]. Of these, the Meuse has a similar pattern, and it was shown earlier that the variance in the apparent ages derived from $^{10}$Be makes a simple interpretation of the pattern uncertain. Also, increasing values of denudation in areas greater than 10 km$^2$ in the Idaho Mountains (figure 4) matches the second pattern. However, the inference that this sediment is generated in-channel is not supported by the high values of denudation in areas less than 10 km$^2$. Unfortunately, data do not exist for small catchments in the Meuse. There is some evidence here for equilibrium in a particular undisturbed class of catchments, but the sediment sources appear to be both out of the channels as well as in them. Studies of more catchments are required to substantiate the case for equilibrium.

(b) Equilibrium

Very few modern river sediment loads are equal to the various long-term estimates of denudation rate. Most are higher, and a few are lower. Despite the likelihood that modern loads are underestimated, these conclusions appear to stand.

The highest values of the ratio of modern post-disturbance sediment transport to long-term pre-disturbance denudation are in small catchments (figures 3 and 6) but there are also many cases of low rates in small catchments. The former are consistent with high SDRs in small catchments and the latter may be as well dependent upon the presence of sediment storage. At least the high values of the ratio are evidence of disequilibrium, supported by calculations of global fluvial sediment budgets showing that about 66 per cent of modern sediment eroded as a result of human activities is yet to reach the global oceans. Also, detailed sediment budgeting in individual catchments shows that the inputs from sources do not equal outputs at catchment mouths because of substantial storage as colluvium and alluvium. Most modern SDRs are much less than 50 per cent.

Over time periods of $10^3$–$10^6$ years, SDRs do not reach 100 per cent. The average global SDR over the longest period is only $69 \pm 4$ per cent, not surprisingly given the existence of depositional basins in many areas as a result of subsidence of the crust.

In previously glaciated terrains, disequilibrium of a different kind occurs. The release of huge amounts of sediment during deglaciation not only produced a time-dependent pulse but also has deposited large amounts of sediment along
rivers downstream of the areas of the former glaciers. It is this sediment that is being reworked, with the paraglacial phenomenon persisting for up to $10^5$ years. Human activities appear to have little impact on such rivers, and management to reduce sediment loads, for example, may have little effect.

The one case where there is (meagre) evidence for equilibrium is in undisturbed forested catchments at high latitudes. The disturbance of these catchments appears to produce the same kind of disequilibrium seen at other locations around the world. If the pre-disturbance state can be verified as one at equilibrium, it could serve as either a reference condition or a target for catchment management.

Presumably modern rivers and their catchments are trending to an equilibrium state as the major pulses of sediment generated by human activities make their way into floodplains and to the global oceans. This conclusion assumes of course that there is a pulse of the kind conceptualized by Schumm & Rea [11] in which disturbance causes a major increase in sediment yield, after which yield declines to a level that is likely to be higher than the pre-disturbance one. An alternative model is that sediment yield remains high rather than declining, a trajectory best described as a step function. Along the way, the increased sediment load in some rivers causes aggradation, channel widening and erosion of floodplains, the net effect of which on sediment yields is unknown. As has occurred in the past, but for different reasons, the trend to equilibrium is likely to be interrupted by other changes such as further land use change, construction of dams and downstream channel erosion resulting from sediment starvation, removal of dams and climate change induced by global warming. Anticipating the results of these processes and phenomena quantitatively is dependent not only upon scenarios of future human activities, but also upon a plausible model of sediment travel times in catchments and rivers. Neither currently exists.

The evidence assembled here provides little comfort to those searching for equilibrium. There is only one case where it might exist. This is in sharp contrast to the geomorphic literature on catchment processes and responses to change, which is littered with references to equilibrium, almost all of which are offered without justification or elaboration. Unless sound evidence can be adduced to the contrary, it must be concluded that rivers and their catchments are permanently in transient states. This is most readily understood by employing Phillips’ [61] relaxation/duration ratio (RDR),

$$\text{RDR} = \frac{R_t}{\Delta t},$$

where $R_t$ is the relaxation time, that is, the amount of time taken to complete a response to a disturbance, and $\Delta t$ is the duration of an event that produces a response. If the RDR $> 1$, there is insufficient time for relaxation to be completed before another disturbance event occurs. It seems that there are too many disturbances to rivers and their catchments (climatic, tectonic and human) to achieve an RDR $< 1$.

The first main conclusion of this paper is that the quantitative differences between pre- and post-disturbance sediment yields are large mostly in small catchments and are buffered by floodplain and in-channel deposition in large catchments. Therefore, in large catchments, over large areas and globally the
range of increase in sediment yield from pre- to post-disturbance is relatively narrow, between 1 and 6. This increase is likely to be felt in larger catchments in the future as waves of sediment move downstream, but the tools to anticipate this phenomenon are not yet available. If a future equilibrium state could be assumed, the task of anticipation of the effects of these waves of sediment would be eased. Equilibrium turns out to be illusory both in the past and in the present, with one possible exception, and explained by the RDR.

This is the second main conclusion of this paper. Therefore, reference or target states cannot be equilibrium states and they can be expected to change, possibly significantly. Herein lies a political risk, whereby natural resource managers cannot guarantee that a restored or even rehabilitated catchment will not change in ways that the community might find objectionable. Also, non-equilibrium models are needed to anticipate future changes, based on the assumption that rivers and their catchments attempt to reach equilibrium but rarely if ever make it. This additional conclusion raises questions about the relationship between process–response formulations, of the kind underpinning the analysis in this paper, and concepts of self-organization, where a quantitatively wide variety of responses occur in response to the same force [62].

How, then, should the concepts in the title of this paper be dealt with? While all catchment management plans should include historical analysis to define the path to the current state, the causes of that state, targets for restoration and rehabilitation, and evidence for equilibrium (although this appears to be illusory), each catchment presents different challenges that require tailored solutions and historical analysis. Fortunately, there is now a toolkit to choose from, including analysis and modelling of measured river sediment loads, substitution of space for time using the comparison of modern disturbed and undisturbed catchments, sediment budgeting, palaeoenvironmental reconstructions and modelling of the records in sediment sinks, sediment transport rate calculations (and their spatial patterns) using the $^{238}$U decay series and cosmogenic radionuclides, and SDRs to determine the degree of disequilibrium.

The sediment transport rates calculated from the $^{238}$U decay series appear to have the least utility because they are never likely to be attained, as perturbations are too frequent to allow relaxation to be completed. Substitution of space for time is only likely to be appropriate if all or most other variables other than the degree of disturbance are constant. Also, the apparent ages of the denudation rates derived from cosmogenic radionuclides can vary widely in the same catchment, making the analysis of the causes of spatial patterns uncertain.

It has been shown that rivers and their catchments are permanently in transient states, and equilibrium is never attained. Yet the fundamental property of an equilibrium system is that it is maintained by negative feedbacks, an idea that catchment management should embrace. The buffering of sediment yields by floodplains in large catchments suggests that floodplains provide the most significant negative feedback. If sediment yields are to be reduced, then floodplains should be managed to absorb as much sediment as possible. This may mean the maintenance of hydraulic roughness through vegetation.

Finally, some of the ideas, data and analyses presented in this paper have already been used in catchment management. Others may appear to be too esoteric for serious consideration, but the only way to know is to try them.
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