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Classification of geomorphological effects downstream of dams

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Abstract

The effects of dams on downstream geomorphology are reviewed and a typology is devised, consisting of nine cases. The classification can be seen as a further development of Lane's balance between water discharge, sediment load, grain size, and river slope. Depending on changes in released water flow and changes in released sediment load, relative to the transport capacity of the flow, it is possible to estimate resulting cross-sectional geomorphology. The longitudinal extent of changes and their variability with time, and the tributary response to altered mainstream cross-section changes, are also discussed. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The number of publications on the effects of dam construction on the environment around the world has increased as dam construction has increased. In 1900, there were 427 large dams, i.e. higher than 15 m, around the world, while in 1950 and 1986, there were 5268 and about 39,000, respectively (ICOLD, 1988). At the same time, the awareness and understanding of variable effects due to the different types of impoundments have grown. During recent decades, dam building has increased especially in areas with extreme conditions of warm climate, high precipitation rates, and intense soil erosion. The regions with the largest increase of large dams during the period 1975–1990 were Central and South America, Asia, and Oceania (Gleick, 1993). Because of short

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reaction times for systems to adjust to new conditions, changes occur rapidly, and their interpretation is relatively easy and new knowledge has been generated within the field of fluvial geomorphology.

Reviews of general effects of dams can be found in, for example, Volker and Henry (1988) and Morris and Fan (1997). Barrow (1987) dealt with the effects of dams and reservoirs in the tropics, and Xu (1990b) with effects on the upstream reaches. Thorough reviews on geomorphological downstream effects of dams have been published by, for example, Petts (1979, 1984a), Williams and Wolman (1984), and Carling (1988). From these reviews, it can be seen that earlier studies of the impact of dams and reservoirs have predominantly been focused on the effects of general scour of the main channel below the dams (Petts, 1979) because of engineering implications, while more recent research has focused on particular conditions downstream of dams, for example at tributary entrances, etc. Other works that describe downstream geomorphological effects include those of Petts (1980, 1982) and Gregory (1987); Petts (1982) also included comprehensive discussions on aggradation below tributaries. Petts and Lewin (1979) and Higgs and Petts (1988) reviewed the effects of river regulation in the UK, Galay (1983) discussed degradation problems, Zhou (1996) summarized the effects downstream from dams in China, and Brandt (2000) discussed the prediction of geomorphological changes in the downstream reaches after dam construction.

To the author's knowledge there has been no classification system of downstream changes due to impoundment. Since many articles have been published after the reviews by Petts and Carling, the objective here is to synthesize these recent findings, from downstream reservoirs around the world.

2. The input from dams on downstream reaches

There exists a great variety of dams and reservoirs with great differences in flow release policies. The difference in dam inputs to the downstream reaches introduces changes to the hydrological regime that will vary from dam to dam. This input can be divided into a water flow part and a sediment flow part, both of which will interact with the downstream channel boundary. The relationship between the flow's transport capacity and released sediment load from the reservoir, together with the relationship between the erosivity of flow and the erodibility of the river banks, should determine changes that, in the long run, produce new stable conditions.

2.1. Water discharge

The effects upon the hydrological characteristics of the river downstream are primarily related to the morphometry of the reservoir, spillway characteristics, and by the operation of reservoir releases (Petts, 1984a). Most often, dams are constructed for one or more of the following purposes: flood control, electric power generation, irrigation, sediment control, municipal supply, and industrial supply. Common to most of them is the reduction of flow, and also, therefore, reduction of stream power and related sediment-carrying capacity, as the result of storage abstraction and by evaporation from the water surface. Peak discharges are also commonly reduced. Some dams may release almost no water at all, while others do not change the releases to any great extent, as compared to pre-dam conditions. All dams affect the natural water discharges in some way, besides during extreme floods when only the major flood regulation dams have any major effect on the water flow (Higgs and Petts, 1988). In this study, the conditions are described as if there were only one dam impounding the river, but, besides the character of the dam construction that may affect the flow in different ways, the number of dams may also play an important role. For example, the effects of individual weirs (small dams built across a river with water flowing over it) may be comparatively small, but the combined effects of successive weirs may be substantial, even exceeding those of dams (Thoms and Walker, 1993).

Decrease in water discharge may also occur downstream from dams where water has been diverted to other watersheds, leading to increased water discharge in the receiving river. Examples of diversions can be found in Sammut and Erskine (1995), from an area in Australia, where regulation and complex diversions of rivers have changed the natural flow schemes.

Besides changed water quantities released and reduction of incoming flood peaks from upstream, a completely different diurnal and annual pattern of flow may occur. Diurnal changes may occur because during daytime, more water is used for electricity generation than during nighttime, and annual changes may occur because during rainy seasons the reservoirs are filled with water for later use in dry seasons. Another characteristic of many regulated rivers throughout the world is the sudden fluctuation of discharges (Petts, 1984a).

The dominant channel forming discharge is often assumed to be the bankfull flow. Knighton (1998) argued that since it seems reasonable to suppose that river channels are adjusted, on average, to a flow that just fills the available cross-section, the dominant discharge, i.e. the discharge that will give the same effects as the whole range of discharges occurring, has been equated with bankfull flow, thereby giving it additional morphogenetic significance. Harvey (1969) stated ‘‘channel capacity must ultimately be governed by a balance between the erosive forces associated with high discharges and the aggradational processes together with vegetational growth associated with lower discharges’’. This balance may be maintained by the annual flood in rivers with accentuated peak flows but by very rare events in rivers with important baseflow (Harvey, 1969). Scheuerlein (1995) defined dominant discharge as ‘‘the discharge for which the product of sediment transport ability and duration becomes a maximum’’, and suggested that the product of magnitude and duration should be used.

As a measure of changes of flow, Benn and Erskine (1994) proposed that water discharge should be described by standardized percentage change, P_c,

$$P_c = 100\left(\frac{X_2/X_1}{Y_2/Y_1} - 1\right) \tag{1}$$

which is the standardized percentage change of mean daily discharge of a given duration. X_1 and X_2 are the mean daily flows of a given duration at the investigated place for pre- and post-dam periods, respectively, and Y_1 and Y_2 are the mean daily flows of a given duration at a control station, not influenced by dam, for pre- and post-dam periods, respectively. Such a description of flow may indicate direction of changes, as in for example the lower Kemano River, Canada, a highly active gravel river, where Kellerhals (1982) reported that widening and straightening had occurred due to tripling of the mean flow, but without a significant increase in largest flood. This means that intermediate flows can do a considerable part of the work and that not all attention should be focused on bankfull flow.

2.2. Sediment discharge

Not only is the water discharge affected, but so is the sediment transport. Depending on the size of the reservoir, large amounts of sediment will be trapped, releasing only a proportion of the former load into the downstream reaches. According to Williams and Wolman (1984), the trap efficiency of what they call large reservoirs is commonly greater than 99%, whereas smaller reservoirs generally have lower values. Trap efficiency is often predicted by the curve by Brune (1953), which is based on reservoir capacity and inflow. As well as reduced load and concentration, a decrease in grain size of the released sediments would be expected to occur. Depending on the reservoir location, the trapping of sediment, especially in tropical and arid regions with prevalent soil erosion, frequently disturbs the fluvial system both upstream and downstream from the reservoir. Even if the reservoirs trap most of the sediment, this does not necessarily mean that the water downstream of the dams will be relatively clear. Other factors within the river system can conceal the dam impacts. Olive and Olley (1997), for example, found at some distance downstream of the Burrinjuck and Blowering Reservoirs on the Murrumbidgee River, Australia, that one third of the annual water flow had been abstracted after dam closure, while only one fifth of the sediment load had been removed. This occurred due to sediment input from tributaries downstream of the dams.

Density currents may be released from the reservoir with high sediment loadings of the downstream reach, but the sediments in these currents are usually so fine that they do not take part in the formation of river channels (Chien, 1985). Such raised downstream sediment concentration has been observed during bottom-gate releases, where the sediment content of the released water to the river downstream may be much higher than those of natural floods (Leeks and Newson, 1989). These events clearly show the importance of the choice of dam-outlet gates on sediment delivery when releasing flow. Sediment transport is also affected by water quality changes, such as thermal change (Webb and Walling, 1996), which will influence the sediment-carrying capacity of the flow.

To increase the lifetimes of reservoirs with high sedimentation rates, different types of desilting techniques can be used. Among these, the techniques of sediment sluicing and flushing are the most common and of great importance to the downstream reach. Sediment sluicing means that sediment is carried downstream with the running water through the reservoir and the dam outlets before it deposits in the reservoir, either by density current or by open channel flow under backwater effect due to the dam. Sediment flushing involves erosion of already deposited sediment and transportation of these through the outlets of the dam (Yoon, 1992). During flushing the water level in the reservoir is lowered to increase the flow's erosivity. Therefore, considerable amounts of sediment may be delivered to the downstream reach altering the *normal* downstream effects of a dam. During sluicing, the sediment transport rates are equal to those of natural flows, and during flushing the rates are equal or higher than those of natural flows.

3. At-a-station changes in the downstream reaches

3.1. Response of the fluvial system

Alluvial channels are generally considered to be systems in equilibrium, where the system responds to input changes by negative feedback, or quasi equilibrium with the adding of a time lag between the change in the process input variable and the internal morphological adjustment of the system (Richards, 1985). Petts (1987) grouped the effects due to impoundment into three orders. First-order changes occur in sediment load, water discharge, water quality, plankton, etc., all describing the input to the downstream reach from the dam and reservoir. Second-order changes are changes of channel form, substrate composition, macrophyte population, etc., and third-order changes are changes in fish and invertebrate populations. Biotic responses are usually faster than abiotic ones and will therefore follow the physical recovery process closely (Petts, 1987); third-order biotic variables can change before any changes have been noticed on the second-order physical variables, and after that adjustments occur continuously until the river system has entered a new equilibrium. An example of use of this system can be found in Benn and Erskine (1994), who evaluated changes on the Cudgegong River below Windamere Dam, Australia.

Cross-sectional channel shape adjustment, which can be regarded as the physical part of Petts' second-order changes, will occur due to the new water discharge and sediment load conditions. This will involve changes in width, depth, and bed level of the channel and, as a secondary effect, change in slope. Associated with slope-, discharge-, and sediment transported changes are changes in bed material, both grain size and the resulting bedforms, planform configuration, pools and riffles, but also response of tributaries to changes in the main stream channel. Of course, it is not only water discharge and sediment concentration that determine channel changes. Several other parameters also affect the system, for example the grain size of transported particles.

3.2. Slope changes

If the trapping effect of the reservoir is significant, fluvial processes will act to reduce the sediment-transport capacity. This is achieved mainly through coarsening of the bed, with a change in slope as an alternative (Chien, 1985). Chien (1985) stated, based on field and laboratory observations, that the slope change due to erosion is usually of minor importance, but if the formation of bed armour is impossible, the adjustment of slope can be significant in order to reduce the transport capacity so it matches the incoming sediment load. If degradation is at a maximum at the upstream reaches below the dam, the slope will flatten as degradation proceeds and simultaneously decrease sediment transport capacity. Furthermore, slope changes may be significant because of changes in river length or sinuosity, but also locally at tributaries due to addition of new debris.

3.3. Cross-sectional changes

The cross-sectional shape can be described by the width/depth ratio which increases with increased stream power and bank erodibility (Robertson-Rintoul and Richards, 1993). Lawler (1992) discussed process dominance in bank erosion systems and concluded that purely hydraulic approaches provide only part of the solution to understanding bank erosion processes. Thorne (1990) ordered several parameters into groups for evaluating the effects of vegetation on riverbank erosion and stability. The first group contains bank parameters, such as height, slope, cohesive or non-cohesive material, etc.; the second group contains channel parameters, such as shear stress of flow on banks, planform, sediment load, etc.; and the third group contains vegetation parameters, such as type, diversity, health, spacing, etc.

As seen above, the bed and bank material is important for the resulting depth and width. The relative erodibility of bed and banks will determine whether erosion will be vertical or horizontal and, mainly, the grain sizes of the transported material together with the hydraulic conditions will determine whether deposition will occur on the bed or on the banks.

3.4. Planform changes

Changes in water and sediment input to the downstream reach may induce a change in planform configuration. Empirically, it has been found that the degree of braiding increases as water discharge is increased for a given slope, or as slope is increased for a given discharge. Increase in energy, and thus shear stress, of flow in a straight low-energy channel, results in bank erosion and meandering of the channel. However, the straight pattern, associated with low-energy flow, is rare in nature. A further increase in energy will result in greater radiuses of bends, the channel thus becoming less sinuous, and finally, development of a braided pattern (Begin, 1981).

Channel pattern also varies with bed-material size. Schumm (1963) found that sinuous channels are characterized by a low width/depth ratio and a high percentage of silt and clay in the channel perimeter. As bed load decreases, a channel becomes narrower and deeper and tends to meander (Sundborg, 1956), and as bed-material grain size decreases, braiding occurs at lower slopes and/or discharges (Bridge, 1993).

3.5. Bedform changes

Changes in grain size are also coupled with changes in bedforms. For example, a plane bed was observed in the Cowlitz River, USA, where dunes normally occur, due to increased slope and decreased bed material size (Bradley and McCutcheon, 1987). Further, it appears that bedforms and bedload movement appear to be related to frequent flows, as compared to channel capacity and meander morphology which reflect more extreme flow events (Richards, 1982).

3.6. Tributary response to main stream changes

The major effect of main stream changes on the tributaries will often be a change in their base levels. An increase of water flow or aggradation, and by that base level raising, will only affect the tributaries up to a level where the backwater curve intersects the original profile (Leopold et al., 1964). For most occasions, however, a lowering of base level due to decreased water flow or degradation could be expected. Several reasons exist for this (Germanoski and Ritter, 1988): (i) Channel bed degradation will lower the flow level of the trunk river at any given discharge; (ii) channel widening by bank erosion of the trunk river will produce the same effect; and (iii) if flow regulation is significant, the peak discharge of the trunk river will be out of phase with the peak discharge of the unregulated tributary streams. The third effect has, for example, been noted in Canada where tributaries adjust by degrading their beds in the vicinity of the junction to the main channel (Kellerhals and Gill, 1973).

The degradation of tributaries after river diversions has, for example, been noted by Pickup (1975) and Kellerhals et al. (1979). Pickup noted degradation because of tributary base-level lowering, due to reduced flow in the main rivers, and creation of a knickpoint at some upstream distance from the confluence of the main river. Schumm's (1973) flume study on base-level lowering showed a progressive upstream erosion of the tributaries with increased quantities of removed material with time. This resulted in aggradation in the newly cut channel. However, as the tributaries eventually became adjusted to the new base-levels, sediment loads decreased and a new phase of channel erosion in the lower reaches of the tributary occurred. Qualitatively, the tributaries studied by Germanoski and Ritter (1988) have responded to lowered base level by headward vertical incision and channel widening. Most obvious were the formation and headward migration of knickpoints. Other effects were sub-aerial exposure of tree roots, crossing the channel above the channel bottom, and presence of terraces of abandoned channel bottoms. The effects were greater near the dam and diminished down river. Vertical incision of the tributaries oversteepened the channel banks and promoted bank slumping, which increased the sediment yield and caused the tributaries to widen (Germanoski and Ritter, 1988).

4. Classification of changes

For analyzing adjustments of river morphology, Lane (1955) expressed the relation,

$$LD \sim QS \tag{2}$$

where D is bed-material grain size, L is transported load, Q is water discharge, and S is slope. It shows that, for example, if sediment load decreases and water discharge does not change, the river bed must become coarser or the slope must decrease. In the

Table 1
Anticipated channel changes due to changed input of water and sediment. Note that the number of references cited should not be seen as an indication of the number of occurrences of each case; it may be biased by the variation of interest in the case studies accessed

	Case 1 $(L<K)$	Case 2 decrease Q $(L=K)$	Case 3 $(L>K)$	Case 4 $(L<K)$	Case 5 equal. Q $(L=K)$	Case 6 $(L>K)$	Case 7 $(L<K)$	Case 8 increase Q $(L=K)$	Case 9 $(L>K)$
Cross-section area	−	−	−	+	0	−	+	+	+
Width	±	−	±	±	0	±	±	+	±
Depth	±	−	±	±	0	±	±	+	±
Bed level	0/D	0	A	D	0	A	D	0	A
Terrace	Formation	Formation	Formation	Formation	0	Disappearance	Disappearance	Disappearance	Disappearance
Riffles	Erosion	Erosion	Erosion/Deposition	Erosion	0	Deposition	Erosion/Deposition	Deposition	Deposition
Pools	Erosion/Deposition	Deposition	Deposition	Erosion	0	Deposition	Erosion	Erosion	Erosion/Deposition
Bedform state	→ low energy state	→ low energy state	→ low/high energy state	→ low energy state	0	→ high energy state	→ low/high energy state	→ high energy state	→ high energy state
Planform state	→ low energy state	→ low energy state	→ low/high energy state	→ low energy state	0	→ high energy state	→ low/high energy state	→ high energy state	→ high energy state
Number of case studies cited	4	3	2	4	0	4	1	1	2

Bedform state is described as a continuum from low-energy flow regime flat bed, over ripples, dunes, and plane bed to antidunes, pertaining to high-energy flow regimes.
Planform state is described as a continuum from straight with low energy over meandering and braided to straight with high energy.
$(-)$ signifies decrease, (0) no change, $(+)$ increase; $A=$ aggradation, $D=$ degradation, $K=$ transport capacity, $L=$ sediment load, and $Q=$ water discharge.

following text, his approach is explored further to deal with cross-sectional effects due to dam construction on alluvial rivers. The effects are grouped into nine cases according to change in water discharge, Q, and the change in relationship between sediment load input, L, and sediment-transport capacity of flow, K. By using a sediment-transport equation to calculate K from water discharge, Q, the relation between load and transport capacity can be determined. Resulting geomorphological impacts are shown in Table 1, the schematic in Fig. 1, and Figs. 2–4 for some of the most common cases. These effects can be regarded as the physical part of the second-order changes in the trunk river, according to Petts (1987). Prior to dam construction, the load transported and the transport capacity of the flow is thought to be equal, as in alluvial channels under equilibrium conditions. The water discharge is thought to be the dominant water discharge, i.e. the discharge that will give the same effects as the whole range of discharges occurring (see Section 2.1).

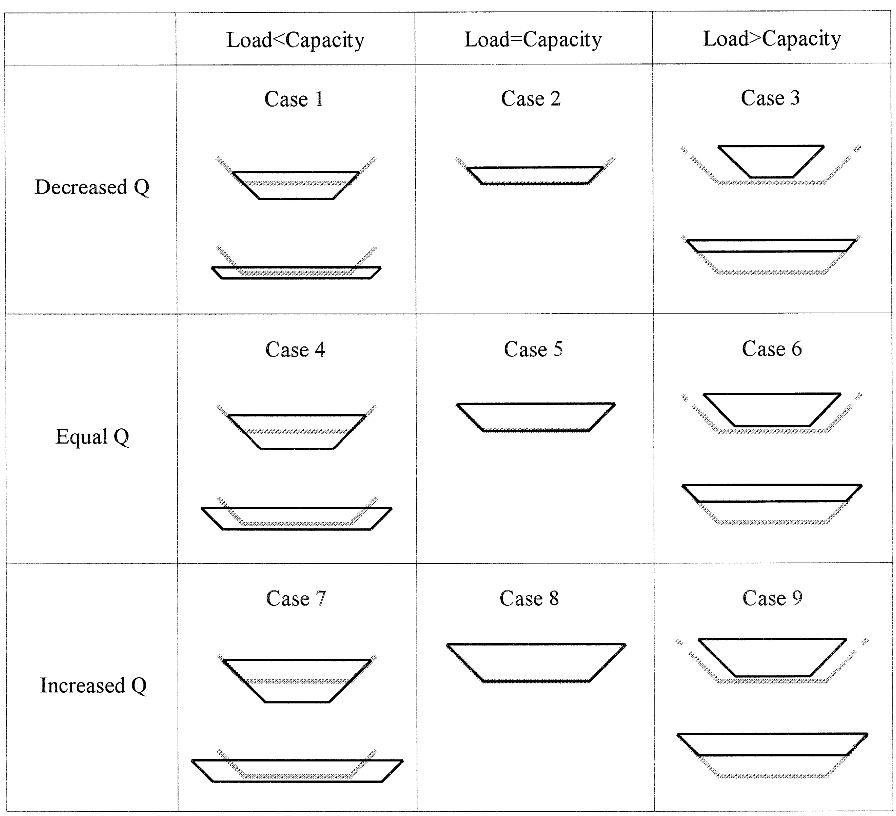

Fig. 1. Schematic examples of possible resulting cross-sectional geomorphology, after changes in water discharge, Q, and relation of sediment load to sediment transport capacity. Gray lines signifies cross-sections before the dam construction and black lines after the dam construction. Note that in Case 1, degradation may not occur if the reduced water discharges are not capable of eroding and transporting the bed material, even though the full flow capacity is not used.

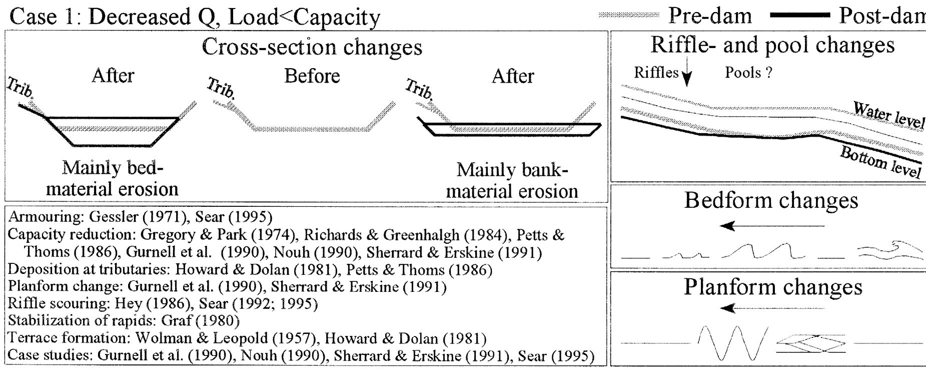

Fig. 2. Expected changes when water discharge decreases and the transported load is less than the flow's carrying capacity (Gessler, 1971; Sear, 1995; Gregory and Park, 1974; Richards and Greenhalgh, 1984; Petts and Thoms, 1986; Gurnell et al., 1990; Nouh, 1990; Sherrard and Erskine, 1991; Howard and Dolan, 1981; Hey, 1986; Sear, 1992, 1995; Graf, 1980; Wolman and Leopold, 1957).

4.1. Case 1: decreased Q and L < K (Fig. 2)

Cross-section changes downstream of dams after decreased water discharges, Q, have been noted by, for example, Gregory and Park (1974). After a reduction to 40% of pre-dam water peak discharges, channel capacity was reduced by 54% downstream the Clathworthy Reservoir on the River Tone, UK. Capacity reduction persisted at least down to where the flow drained an area four times the drainage area of the reservoir. However, Williams and Wolman (1984) have found that decrease in daily discharges and in peak discharges do not automatically mean reducing cross-sectional areas. That is, these flows do not adequately reflect the erosive flows. However, if the flow becomes sufficiently small, it will only use the deeper part of the old channel, and vegetation can establish on the rest of the old channel, which develops into floodplain (Williams and Wolman, 1984).

Because the load, L, in Case 1, is less than the capacity of the flow, K, some degradation may occur if the bed material is fine-grained, but it is also likely that the reduced water discharges are not able to erode and transport the material present before dam construction. However, the finest material may still be available for transport, resulting in armouring; the surface becomes relatively coarser than the underlying material. Ultimately, the cross-sectional shape of the channel will be determined by the relative erodibility between channel bed and bank material. Petts (1979) has noted the lack of degradation in channels below British reservoirs that are cohesive, well vegetated, or lined with coarse sediments (with regulated discharges often well below the values for sediment transport). Under these conditions, only reduction in frequency of bankfull flows occurs. Also, Kellerhals (1982) has not noted any significant channel degradation downstream of major storage dams on gravel-bed channels, due to the reduced ability of the post-regulation flow to move its bed material. The reduced water discharges will also decrease the flows' capability to transport introduced sediments from tributaries, even if the flow has an overcapacity. The result will be formation of a tributary deposition or increased extent of already existent deposits.

4.2. Case 2: decreased Q and L = K (Fig. 3)

As with Case 1, the decreased water-flow input from upstream will lead to decreased depth and width, accompanied by the creation of terraces and new floodplain from the parts of the channel that have been left dry. With the implication that the load carried matches the carrying capacity, degradation and armouring are not likely to occur, tributary deposition is expected to be somewhat more extensive than in Case 1, and riffles should not be subjected to intensive scouring, whilst deposition in pools increases. Rapids are also likely to get more stable.

As noted by Petts and Lewin (1979), true reduction of channel capacities (not merely transformation of parts of the old channel into terraces and non-active floodplain) requires the introduction of sediment by tributaries and/or redistribution of sediment within the channel. The removal of flood peaks means that the sediment supply from the tributaries will also increase due to an upstream migrating erosional front of the tributary when the tributary base level is lowered (Petts, 1979). After reservoir construction on the river Rheidol, UK, Petts (1984b) noted deposition below a tributary confluence. The new channel, close to the confluence, is narrower and relatively deeper with improved sediment transport capacity. Generally, not only material derived from tributaries is deposited, but also some material from the main stem river flow. Usually, this occurs immediately downstream of junctions, in flow separation zones.

4.3. Case 3: decreased Q and L > K

As with the previous two cases, the cross-sectional area of river flow will decrease by reduction in width and/or depth because of reduced water discharges. Due to overloading of flow, material will be deposited leading to aggradation, probably with associated features of channel multiplication and bar deposition (Hoey and Sutherland, 1991). Due to deposition, the area of the old channel is decreased. Whether the sediment will be deposited on the bed or at the banks depends largely on the grain size of the transported

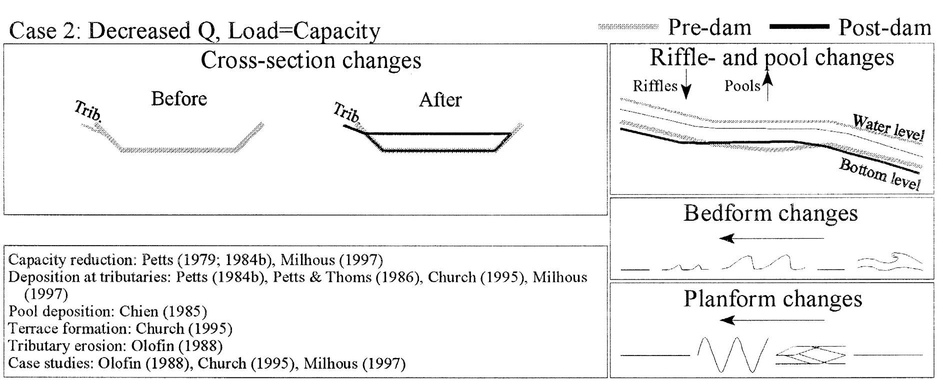

Fig. 3. Expected changes when water discharge decreases and the transported load equals the flow's carrying capacity (Petts, 1979, 1984b; Milhous, 1997; Petts and Thoms, 1986; Church, 1995; Chien, 1985; Olofin, 1988).

sediment. Coarse-grained material tends to deposit on the bed while fine-grained material tends to deposit at the sides of the channel. Increased deposition rates are expected, both at tributaries and in pools. Depending on the degree of overloading, deposition may occur at riffles and rapids.

The case with decreased water discharge, *Q*, and load, *L*, exceeding capacity, *K*, may seem unusual but exists, for example, if the sediment transported by the river is allowed to pass through the reservoir dam. A common reservoir type in China is that of flood detention whose purpose is to relieve the downstream area from the threat of flooding. When the flood recedes, the stream channel in the reservoir will resume its natural state. During the recession of the flood, most of the sediment deposited in the preceding stage will be eroded and sluiced out from the reservoir (Chien, 1985). Therefore, the positive correlation between water discharge and sediment concentration in alluvial rivers does not exist below flood-detention reservoirs. Low and medium flows after a flood, already saturated with sediment, are loaded with an additional supply of sediment eroded from the reservoir. Material exceeding the capacity of the flow will be deposited in the channel, particularly in the upper part of the reach. Due to the reduction of the flood peaks, the probability of floodplain flows is reduced. The effect is increased siltation of the main channel and raising of the bed, reducing the difference between bed and floodplain levels further, making the appearance of the flow more disorderly. Furthermore, if, after impoundment, the deposition of fines occurs on a coarse river bed, it will change its composition (see Einstein, 1968; Beschta and Jackson, 1979; Schälchli, 1995; Petts, 1988 for infiltration of fines into the river bed). See Chien (1985) and Qian et al. (1993) for case studies.

4.4. Case 4: equal Q and L < K (Fig. 4)

The case when only a reduction of sediment load occurs will not lead to any greater changes of the cross-sectional size of flow. However, the cross-sectional shape and

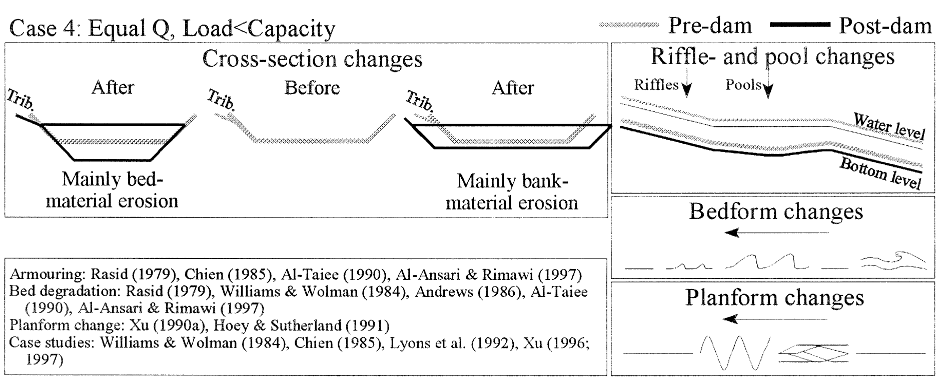

Fig. 4. Expected changes when water discharge does not change and the transported load is less than the flow's carrying capacity (Rasid, 1979; Chien, 1985; Al-Taiee, 1990; Al-Ansari and Rimawi, 1997; Williams and Wolman, 1984; Andrews, 1986; Xu, 1990a, 1996, 1997; Hoey and Sutherland, 1991; Lyons et al., 1992).

position may change. When the water has excess transport capacity, which is the case when transport capacity of the flow is greater than the load, the adjustment of the transverse shape of a graded channel involves two mechanisms (Chien, 1985). One is downcutting by the erosive clear water from the reservoir, which leads to the deepening and narrowing of the river channel. The other is bank caving or undercutting, which leads to widening. As compared to natural rivers, there is a lack of floodplain rebuilding processes, giving net erosion, because of elimination of both sediments and floods with overbank deposition.

Williams and Wolman (1984) stated that the simplest form of degradation is the removal of bars. With further removal of material, this will lead to downcutting and, later, to widening if downcutting is prohibited (Williams and Wolman, 1984). In connection with the degradation process, the formation of an erosion pavement is common. This can occur even if the flow is sufficient to move all available particles in the bed. Later, these newly eroded particles may be deposited on even finer-grained sediments farther downstream, extending the zone of coarse material. Pavement formation will significantly increase bed roughness and lead to increased depth and decreased flow velocity and sediment transport capacity; thus, a slight increase of cross-sectional area might be expected. Whether the result will be increased width, degradation, and/or armouring depends on the relative stability of bank and bed material and the degree of the flows' sediment deficiency.

4.5. Case 5: equal Q and $L = K$

Even though the water discharge, Q, sediment load, L, and transport capacity, K, remain the same after dam construction (as when the reservoir is small relative to the inflowing amount of water), there still exist some possible causes of channel changes. Williams and Wolman (1984) mention diurnal flow fluctuations (power or other controlled releases) causing consistent bank wetting, promoting greater bank erodibility, and rapid changes in flow releases (common with power dams), causing the river to wander indiscriminately from one side of the channel to the other, encouraging periodic erosion on first one bank and then the other, without compensatory deposition.

4.6. Case 6: equal Q and $L > K$

The case when water discharge, Q, is not changed and sediment load, L, is greater than transport capacity, K, is rarely found due to the sediment trapping effect of the reservoir. However, this may occur temporarily during flushing. The sedimentological effects downstream from such reservoirs can be extreme. Large quantities of deposited sediment have been found in the reaches below the Cachí Reservoir, Costa Rica. Prior to flushing very little or no fine-grained sediments were present in the reaches close to the dam (Brandt and Swenning, 1999; Brandt et al., 1995). Boillat et al. (1996) observed similar impacts in a channel that passes water down to the river from the reservoir, downstream of the Gebidem Reservoir, Switzerland.

Due to the different travel times of the water and sediment-concentration peaks, the percentage of within-channel deposition will increase in the downstream direction (Brandt and Swenning, 1999). The effects are: raising of the bed and increased probability of overbank deposition — consequences that may be the reverse of the initial purpose of the dam to decrease the effect of flooding. Similar effects have been noted on the Rio Grande, USA, where water is diverted for irrigation and later redistributed back, but loaded with sediment. Consequently, the channel has diminished in size and can no longer contain floods as large as it once could, with significant damage downstream from the dam (Collier et al., 1996).

Depending on the characteristics of water flow and the transported sediment, the active river channel will either narrow down or shoal due to overloading. If the river narrows, the flow will become deeper, which is a characteristic of most suspended-load rivers. If the river aggrades, water will be forced over existing boundaries with increased water-surface width. Furthermore, raising of the bed level, which will increase slope and possibly decrease grain size and roughness, might give a slight decrease in cross-sectional area. See Doeg and Koehn (1994), Brandt (1999), Brandt and Swenning (1999), and Brandt et al. (1995) for case studies; Bradley and McCutcheon (1987) for bedform change; and Leopold and Wolman (1957), Kirkby (1980), and Chorley et al. (1984) for planform change.

4.7. Case 7: increased Q and $L < K$

When water discharge is increased and the flow is underloaded, the effect must be increased cross-sectional area, partly through erosion of channel bed and banks and partly due to the greater extent of flow (see, e.g. Church, 1995). Former terraces, tributary deposition, and pools will be eroded, while riffles may experience slight deposition or erosion depending on the degree of sediment deficiency. Armouring may occur if underlying material is coarser than the previously eroded channel deposits. Kellerhals et al. (1979) reported increased cross-sectional area as the most common effect from several rivers in Canada that have experienced increased flow due to river diversions. However, increased total water discharge is not a requirement to obtain increased capacity. Petts and Pratts (1983) found below the Leighs Reservoir on the River Ter, UK, a 2-fold increase of channel capacity, dominated by increased channel width, after a 10-fold increase of low-flow discharge. See Kellerhals et al. (1979) for case studies.

4.8. Case 8: increased Q and $L = K$

As in Case 7, increased cross-sectional areas of flow will occur when water discharge is increased (see Kellerhals et al., 1979). Due to matching load and transport capacities of flow, there should not be net erosion nor deposition. Erosion of pools and deposition on riffles may be expected (see Chorley et al., 1984; Hey, 1986) as well as a shift to planform patterns associated with higher flow energies (see Begin, 1981; Carson, 1984a,b). See Kellerhals et al. (1979) for case studies.

4.9. Case 9: increased Q and $L > K$

The situation with increased water discharge, Q, and overloading of flow is very unlikely to occur, but may exist if water has been diverted to the reservoir and is released during flushing, or when an exceptional large flood is routed through the reservoir while flushing. Such flows will increase cross-sectional areas and deposit material, thereby raising the bed level. However, experiences from China show that, if the flow is hyperconcentrated, the effects may be the opposite. Long and Qian (1986) noted that a hyperconcentrated flow passed through the meandering reach of the Wei River without causing any deposition. Furthermore, they noted that when the load surpasses 400 kg/m^3 in the Yellow River, the change in physical properties of the flow causes the flow to maintain a high concentration. Wang et al. (1997) noted that even bed scouring will occur if the flow is hyperconcentrated. See Qi (1997) and Li et al. (1997) for case studies, and Li et al. (1997) details on for planform change.

5. Variability of changes with time and distance from dam

In the above sections, the resulting geomorphology has been discussed at-a-time and at-a-station. Sections 5.1–5.3 deal with how changes vary over time and with distance from the dam.

5.1. Variability with time

Due to altered water flow and movement of sediment by the construction, channel changes usually begin as early as the initial stages of dam construction. Furthermore, deposition of sediment in the reservoir generally begins before the dam is closed officially (i.e., when the dam is put into operation) (Williams and Wolman, 1984). Since it often takes several years to construct a dam, Williams and Wolman (1984) suggested that it would be more logical to look at the date when construction began than the closing date. However, the full effect will not be reached until the closing date. Furthermore, the effects during construction may be opposite to those after dam closure, as Davey et al. (1987) noted on the Thomson River, Australia, where increased downstream sediment transport and deposition occurred close to the dam site during construction.

Of the rivers investigated by Williams and Wolman (1984), one half the total amount of width change could occur in as little as 1 or 2 months after dam closure, i.e. about 5% of the total period the rivers were supposed to change due to dam construction. Most of the rivers reached this amount between 1 1/2 and 2 years. Also for degradation, the largest amounts of sediment removal, to adjust the slope, took place relatively quickly after dam closure. The degradation then diminished with time as the bed became armoured, if the bed did not consist of only fine-grained material of unlimited depth or the slope became too flat. Most of the rivers reached half their total amount of depth change in 7 years. The scatter of the adjustment periods is large for both width and depth. The maximum values for half the amount of changes were 100 years and 340 years for width and depth changes, respectively. The degradation generally ceases within decades or a few centuries (Williams and Wolman, 1984). Generally, however, the degradation is not consistent as time goes on. Usually, temporary periods of aggradation occur within the degradation period and the degradation may have an abrupt end if bedrock is reached or an armour has developed. For the rivers investigated by Williams and Wolman (1984), the initial degradation rates ranged from almost negligible to as much as 7.7 m/year, and degradation mainly occurred within the first 10–15% of the adjustment period.

5.2. Variability with distance from dam

The distance from the dam and the fraction of water flow derived from the dam will, naturally, affect the degree of changes. From rivers in the UK where the impounded catchment area formed no more than 35–40% of the total drainage area, regulation showed no significant effect on the downstream morphology (Petts, 1980). If dam construction leads to erosion of the channel, as in Cases 1, 4, and 7, the downstream

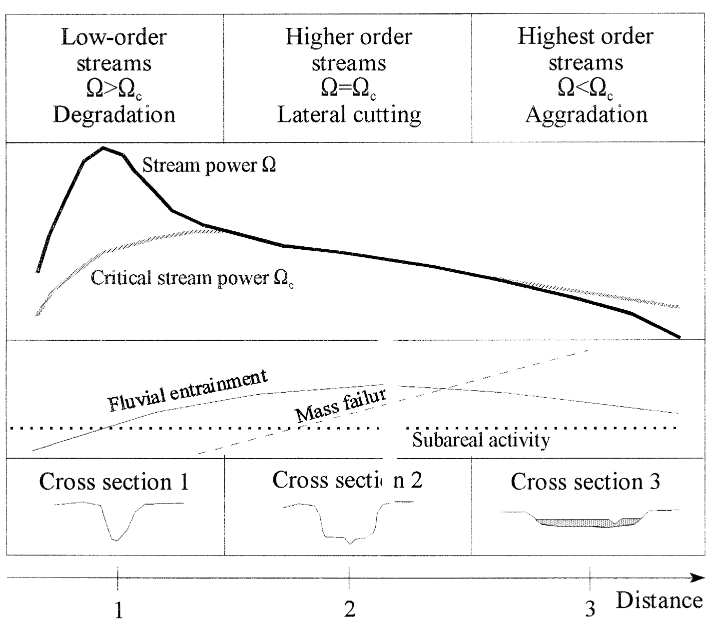

Fig. 5. Figure describing the variability of stream power and critical stream power in an arid and rocky drainage basin (derived from Bull, 1979, 1991) and efficacy of process leading to erosion of channel banks (derived from Lawler, 1992).

recovery of sediment by the flow is greatest near the dam, at least initially, with a progressive shift downstream. Williams and Wolman (1984) noted from the USA that it appeared that the material came from the bed closer to the dam and with a greater relative contribution from banks farther downstream. Bull (1979) explained this with relative stream power. In reaches where stream power clearly exceeds critical power for sediment entrainment, vertical erosion predominates, e.g. in most mountainous regions, while in reaches where the stream is close to the threshold value, lateral erosion predominates. Farther downstream, stream power is usually less than the critical power, leading to sediment deposition (Fig. 5) (Bull, 1979). Furthermore, in the downstream reaches, the flow may be affected by base levels. While the flow near the bottom will be retarded, the flow near the surface may not be so to the same degree. This makes lateral erosion more likely and vertical erosion less likely, due to a decrease in bottom shear stress. Lawler (1992) divided bank erosion processes into three parts (Fig. 5). In the uppermost reaches of the river, sub-aerial preparation processes, such as freeze–thaw, dominate. These processes are thought to be constant along the whole river course. Farther downstream direct fluvial entrainment processes dominate, due to larger stream powers when water discharge increases. In the lowermost parts of the river, the dominating process on bank erosion is mass failure giving retreat of banks.

5.2.1. Width changes

Leopold and Wolman (1957) suggested that the primary adjustment after changed waterflow is changed channel width with later adjustment, within that constraint, of depth, velocity, slope, and roughness. They based this from observations that the latter variables are, apparently, less directly controlled by discharge, and the variation in width between rivers of equal discharge could be related to sediment concentration and the composition of bed and banks. Relative width changes of the US rivers investigated by Williams and Wolman (1984) do not seem to be greater near the dam. Rather, they appear to vary randomly with distance in some rivers or to remain constant in others. For the rivers that had experienced channel widening there were indications that shallow channels increase in width at a somewhat greater rate than do narrow, deep sections. All investigated reaches below hydropower dams had undergone slight widening or practically no change, while reaches below non-hydropower dams (with little or no flow during a large part of the year) had narrowed considerably.

5.2.2. Bed-level changes

Degradation, i.e. the most immediate morphological impact of dam constructions, will extend progressively with time downstream from the dam. Flume studies generally show maximum degradation at or near the dam relative to the total reach undergoing degradation (Williams and Wolman, 1984). Wolman (1967) found, from nine rivers in the USA, that the location of maximum point of degradation varies significantly between different rivers. The location varied between near zero and about 70 channel widths downstream from the dam. Usually, it was found to be slightly removed from the dam, generally not more than 20 channel widths downstream. Why it is found at a distance downstream from the dam has not been answered, but it seems possible that the probability is greater if the dam is built on erosion-resistant rock. Williams and Wolman (1984) noted degradation immediately downstream from all the dams of the 21 channels investigated, except where the channels were constricted by very coarse material or bedrock. The migration rate of the downstream edge of the degradation zone varied with flow releases and bed-materials (Williams and Wolman, 1984).

Stabilization of a degrading channel can occur due to a variety of independent and dependent variables (Williams and Wolman, 1984). Concerning the independent variables, stabilization may occur if, for example, bedrock emerges, the channel slope becomes controlled by downstream base level, the inflow from tributaries equals the flows' excess transport capacity, or growth of channel vegetation occurs. The channel may also be stabilized through the change of dependent variables, such as, development of armour by winnowing of fines, decrease in flow competence by slope flattening, increase in channel width resulting in decreased depth and/or redistributed flow velocities, or increase of sediment inflow from tributaries due to base-level lowering in main river. In the downstream reaches, below the point of stabilization, the degradation may then be succeeded by aggradation (Williams and Wolman, 1984).

Following Chien (1985), the process of degradation in alluvial rivers can be described as follows (Fig. 6): The hypothetical river before dam construction is slowly aggrading due to a slow decrease in sediment transport capacity with a simultaneous decrease in load (Fig. 6a). With the dam in place, the clear water from the reservoir picks up sediments from the channel. Beyond a certain distance, i.e. the distance of concentration recovery, the water flow becomes saturated with sediment, which means that the transporting capacity of the flow is fully utilized. At the beginning of reservoir operation, for example until a bed pavement has developed, this is also the point down to where the river is degrading (Fig. 6b). If bed material is inhomogeneous, the river bed is coarsening during this process, giving lower transport capacity. This leads to the transported particles becoming fewer and coarser. However, downstream from the concentration recovery point, plenty of fine-grained material is still available in the bed. Due to the bed-material transport capacity of the flow exceeding the incoming load, further erosion downstream from the old concentration recovery point will take place. In short, due to a limited supply of sediment and the increased roughness in the uppermost reach (giving reduced transport capacity), the clear water released from the reservoir takes a longer distance to obtain the same sediment concentration. This implies that the location of the concentration recovery point shifts upstream and the point down to where degradation occurs, shifts downstream as with the maximum degradation rate point (Fig. 6c, d, and e). Further downstream, both the supply of fine particles from the bed and the sediment transport capacity of the flow, increase progressively with distance. This sediment-concentration increase with downstream distance from dam has been noted during controlled reservoir releases by, for example, Beschta et al. (1981) and Gilvear and Petts (1985).

If the downstream effect is channel aggradation, this will continue until the slope is steep enough to provide the velocity required to transport all the debris delivered to the stream (Mackin, 1948). If channel-side depositions of coarse material do narrow the channel and confine the flow, thus permitting sediment transport through the reach; this allows for the depositional front to develop progressively downstream (Petts, 1979).

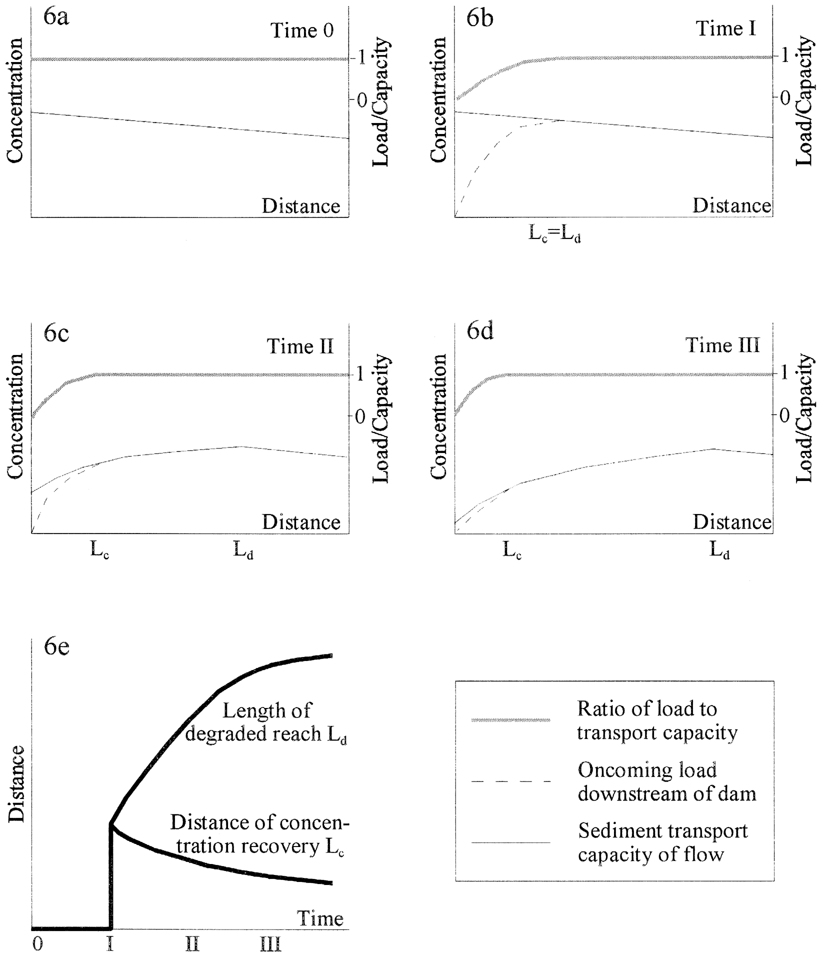

Fig. 6. Figures based on Chien's (1985) reasoning on distance of concentration recovery, L_c, and distance of degraded reach, L_d, during a time series. 0 represents the period before the dam is put into operation, and I, II, and III are the chronological times after the dam is put into operation.

5.3. The classification system with increased distance from dam

As an example on the use of the classification system, a hypothetical river with a fairly normal appearance is shown in Fig. 7. The dam is located in a mountainous region where slopes are high. At some distance downstream, the slope flattens and the river becomes braided. Downstream from the braided area is a local base level, whereafter the slope becomes high again and the channel becomes straight. Further downstream, the river again becomes braided and close to the sea it begins to meander. Usually in mountainous regions, the bed material is of gravel and stones, while in flatter areas it is

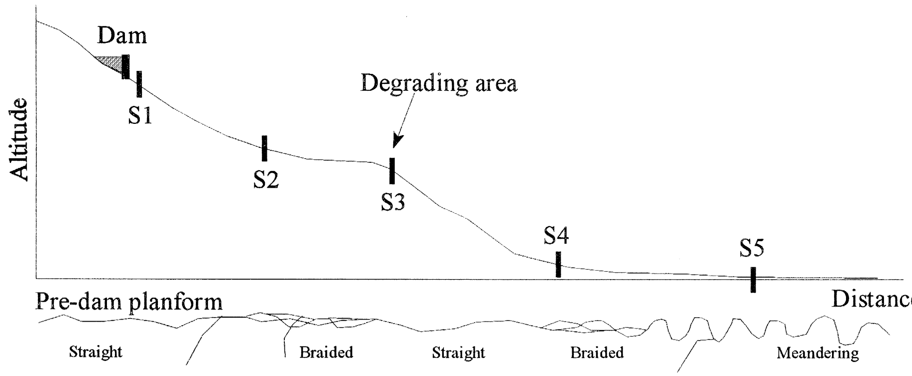

Fig. 7. Hypothetical river profile.

of sand and silt. In this example, the region at the knickpoint in slope is subjected to degradation, indicating that the system is not entirely at equilibrium conditions.

Depending on the amounts water and sediment released, and where in the profile we are located, different cross-sectional changes can be expected. In the example, three common cases are used. Case 1, where water discharge is decreased and released load is less than the transport capacity (common with reservoirs for irrigation); Case 4, where water discharge is not changed and released load is less than the transport capacity (common with reservoirs for electricity generation); and Case 6, where water discharge is not changed and released load is greater than the transport capacity (common for reservoirs subjected to flushings) (Fig. 8).

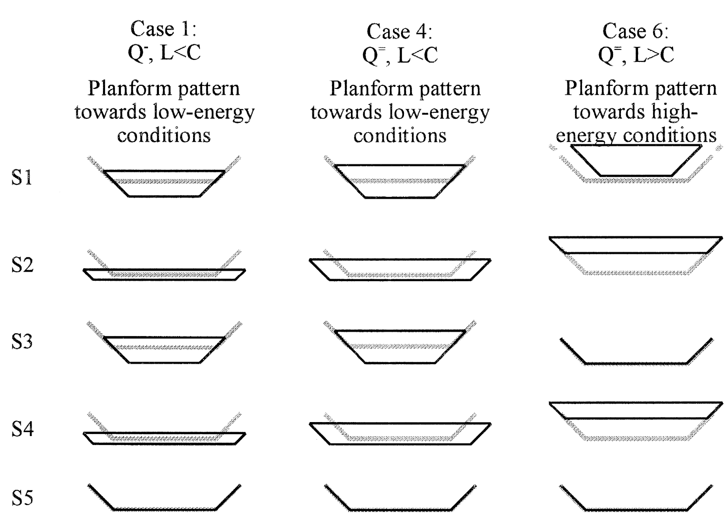

Fig. 8. Probable effects in the hypothetical downstream reach for three different inputs of water and sediment.

In Case 1, the clear water released from the reservoir will in the uppermost reaches erode mainly the bed of the river channel, unless the flow is so much reduced so shear stresses and velocities are unable to move the bed material (S1, Fig. 8). Farther downstream, the banks will be more eroded than the bed (S2, see also Fig. 5). Erosion in the upper reach, above the knickpoint in slope, will continue until the slopes are lowered enough or an armour layer has developed. At the knickpoint, erosion will occur as it did in the pre-dam period (S3). If the flow's transport capacity has not been filled by erosion of bed and bank sediments in the upper reach, some erosion will take place around S4. In the lowermost reach, no effects will be seen if the enough erosion has taken place (S5). The tributaries will feed the river with both water and sediment, whereby the relative influence of the dam will be less pronounced, i.e. with reduced amounts of changes, with increased distance from the dam. Case 4 will show similar changes as Case 1, only with a more pronounced erosion due to higher water flows and with a sustained pre-dam cross-sectional area of the flow.

In Case 6, due to overloading of flow, the relatively fine material from the flushing will be deposited in the upper reaches. Furthest upstream much of the deposition will take place as bank deposition (S1), while further downstream most will be deposited as bed deposits (S2). The latter is due to the time lag between transported water and sediment. Most of the deposition around S2 occurs at water levels less than bankfull levels, because the water peak has already passed. The amount of deposition is also likely to decrease in the downstream direction due to decreasing overloading (as well as due to introduction of more water from tributaries). At the knickpoint, deposition may be hindered or erosion may occur due to the steeper slopes (S3). All material from the flushing that deposits in this reach with high slopes, has probably already been deposited in the reaches upstream from the knickpoint in slope (S1 and S2). This is also the case for S4. Material found deposited there must therefore come from eroded deposits around S3. Upstream from S5 water discharge is increased by tributary inflow and the balance between water and transported sediments is regained; thus, zero or only slight deposition can be expected close to the sea. Note, however, that the deposits in the upper reach probably will be eroded by later clear-water releases from the dam and be deposited in the flat area above the knickpoint in slope and in the flat areas close to the sea.

6. Confirmation of channel changes

When evaluating whether channel changes can be attributed to the construction of dams, pre- and post-dam measurements at an upstream control site can be informative. This may give more certain results compared to just looking at the downstream parts. Because of small changes in elevation, even though the amount of eroded material is great, several years of measurement would be needed to get reliable results, not significantly affected by natural short-term changes. Wolman (1967) estimated that about 10 years of record would be needed to show a degradation rate of 0.08 m/year and 30 years to show a degradation rate of about 0.01 m/year based on measurements from the Missouri River, USA. Gregory and Park (1974) plotted and regressed channel capacity against catchment area along the river Tone, UK, with the Clathworthy Reservoir. Based on extrapolation of upstream-from-dam capacity values, a distinct discrepancy between measured and predicted downstream-from-dam channel-capacity values clearly showed the influence of the reservoir. From this, the channel capacity below the dam could be estimated to 54% of original capacity.

Williams and Wolman (1984) described several criteria for confirmation that channel changes, on the investigated rivers in the USA, are due to dam constructions. (i) Degradation is greatest at or near the dam, (ii) the relation between water-surface elevation to discharge for a reference low flow indicates that the channel generally was relatively stable prior to dam construction, (iii) there is a tendency for the river bed to erode downstream from a dam, whereas the river bed upstream from the dam does not change, and (iv) extrapolation of degrading channels back into pre-dam years gives streambeds at unrealistically high elevations.

When evaluating the effects of dams, care should be taken so that not all effects are addressed to dams and reservoirs. On the Arno River, Italy, for example, severe degradation has occurred due to a combination of reforestation, bed material mining, and construction of two upstream reservoirs (Billi and Rinaldi, 1997), and in the Arve River, France, degradation occurred due to a combination of gravel extraction, weir construction, and embankment (Peiry, 1987).

Other criteria, aside from elevation and channel capacity, for the confirmation of channel changes could be change in grain size, both at one location as well as along the river, or change in the planform configuration. Indirectly, biological change in the river eco-systems, such as changed numbers of taxa and individuals, could also indicate changes due to dam construction.

7. Conclusions

From the review, it can be seen that the effects downstream from dams differ greatly depending on location, environment, substrate, released water and sediment, etc. By using Table 1 and Fig. 1, based on changes in released water flow from the dam and changes in released sediment load relative to the transport capacity of the flow, a first estimate on what changes could be expected in the downstream reaches can now be made. The changes of released water flow and the relation between released sediment load and the flow's sediment transport capacity, are then supposed to be known or to be predicted if the dam has not yet been constructed. Further, changes downstream from newly-built dams should be easy to anticipate if records on water and sediment flows are available from the pre-dam period.

The examples show that, for the same change of flow, the effects may differ depending on the type of bed and bank material and the grain sizes of the transported material. Therefore, to be able to forecast changes correctly a study should also include grain-size distributions of the released load, the erodibility of beds and banks, as well as an analysis of the existing geomorphology, including variation of slope. The classification may then serve as a starting point for analytical prediction of effects or as a check for the analytical models.

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