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River Channel Processes and Morphologic Change

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Abstract

The form of a river channel can be viewed as the outcome of the continuous struggle between the erosive potential of the river and the resistance of the valley floor materials, hence its channel is not fixed but changes through time. Channel morphology is the result of the combined influence of the independent landscape or external basin control variables and dependent landscape variables, and the channel responds to changes in these variables by adjustments in one or many of the dependent channel variables. This shows that the form of a channel is controlled by driving variables (flow and sediment supply), and boundary conditions (valley slope and confinement, channel substrate and riparian vegetation). The fluvial system is affected by changes in the external basin controls. Changes in the external basin controlling variables-climate, human activity, tectonics/geology and base level influence the whole fluvial system These affect the channel controls, in turn leading to changes in channel form. The channel can adjust to these changes in a variety of ways including changes in channel width and depth, channel cross-section, shape, velocity, slope, roughness, channel gradient, bed material composition, channel sinuosity, sediment size, and bed form composition. In this paper the objective is to review the autogenic and allogenic processes and their consequent channel morphologic changes. Secondary sources of data such as journals, books etc were used in the review

Keywords: River, Channels, Morphology, Processes

Introduction

River channels do not remain fixed in shape or position over time, but change naturally in response to a variety of interrelated variables (Thompson, Ramsey, Mollhagen, Evans, & Lehman, 1997). The form of a river channel can be viewed as the outcome of the continuous struggle between the erosive potential of the river and the resistance of the valley floor materials. The driving force causing water to flow (whether in a channel, rill, gully or overland) is the down-slope component of gravity (Charlton, 2008). This acts on a given mass of water, causing it to deform (flow) and move in a downstream direction over the channel boundary (bed and banks). This movement is opposed by resisting forces and resistance occurs due to friction between the flow and channel boundary. The fluid likewise itself resists deformation because of internal forces within the flow. Water moving downslope exerts a shearing force, or shear stress, on the channel boundary. The bed shear stress τ_o is expressed as a force per unit area of the bed (in N m^{-2}) and increases with flow depth and channel steepness.

The shear stress acting on the bed of a channel is defined by:

$$\tau_o = \rho g h S \qquad (1.1)$$

where τ_o is the spatially averaged bed shear stress, ρ is water density, g is the acceleration due to gravity, h is the depth of flow and S is the slope.

The form of the channel affects the flow of water in it and, through erosion and deposition, and the flow in turn modifies the form. The channel (and often the valley floor) acts as a jerky conveyor belt for the transport of sediment moving intermittently towards the sea.

Streams change in shape or position over time in response to a variety of interrelated variables. Over geologic time channels respond to tectonic uplift, erosion of the landscape, and climate change and over historic time channels respond to changes in discharge and sediment supply from both land use and such extreme events as floods and droughts (Montgomery and Buffinghton, 1993). There is a general sequence of channel adjustments following natural or anthropogenic disturbances that cause streams to have more energy and erode more sediment.

Rivers and streams shape and reform their channels through erosion of the channel boundary (bed and banks) and the reworking and deposition of sediments. . Erosion and undermining of the banks can lead to channel widening. Scouring of the channel leads to channel bed incision, while sediment deposition leads to reduction of the channel depth and to the formation of channel bars (Charlton, 2008).

Channel morphology simply means channel shape. According to Wolman, & Miller,(1964, p.198), “The shape of a cross-section of a river channel at any location is a function of flow, the quantity and character of sediment movement through the section, and the character or composition of the materials making up the bed and banks of the channel and naturally the last will definitely include vegetation”.

Channel morphology is dynamic, changing spatio-temporally in response to controlling factors such as changes in hydraulic discharge, sediment delivery, and stream bed and stream bank roughness (Beschta and Platts, 1986; Montgomery and Buffington, 1998). The channel can adjust to these changes in a variety of ways including changes in channel width and depth, channel cross-section shape, velocity, slope, roughness, channel gradient, bed material composition, channel sinuosity, sediment size, and bed form composition (Leopold and Maddock, 1953).

Channel Processes

Factors controlling channel morphology can be divided into those that are imposed on the watershed (i.e., independent), also called the external basin controls and those that adjust to the imposed conditions (i.e., dependent), also called the channel controls (Charlton, 2008; Hogan and Luzi, 2010). The independent landscape factors or the external basin factors controlling channel morphology are geology, climate, and human activities (Figure 1). The geologic, climatic, and human conditions to which a catchment is subjected determine the dependent landscape variables of sediment supply, stream discharge, and vegetation (Montgomery and Buffington 1993; Buffington et al. 2003). According to Charlton, 2008, changes in the external basin controlling variables- climate, human activity, tectonics and base level influence the whole fluvial system (Figure 2). The implication is that channel morphology is the result of the combined influence of the independent and dependent variables, and the channel responds to changes in these variables by adjustments in one or many of the dependent channel variables. Changes in the external controlling variables-climate, human activity, tectonics and base level influence the whole fluvial system. Channel changes can also occur without any change in the external basin controls or external disturbance and these are called **autogenic changes**. Channel changes that are triggered by the external controls are called **allogenic changes**. Human alteration of the landscape can also significantly change watershed conditions. Therefore, channel morphology or channel shape is a reflection of the processes that formed it. There is a two-way feedback relationship between process and form. In other words, processes shape forms and forms influence the way in which processes operate (rates and intensity).

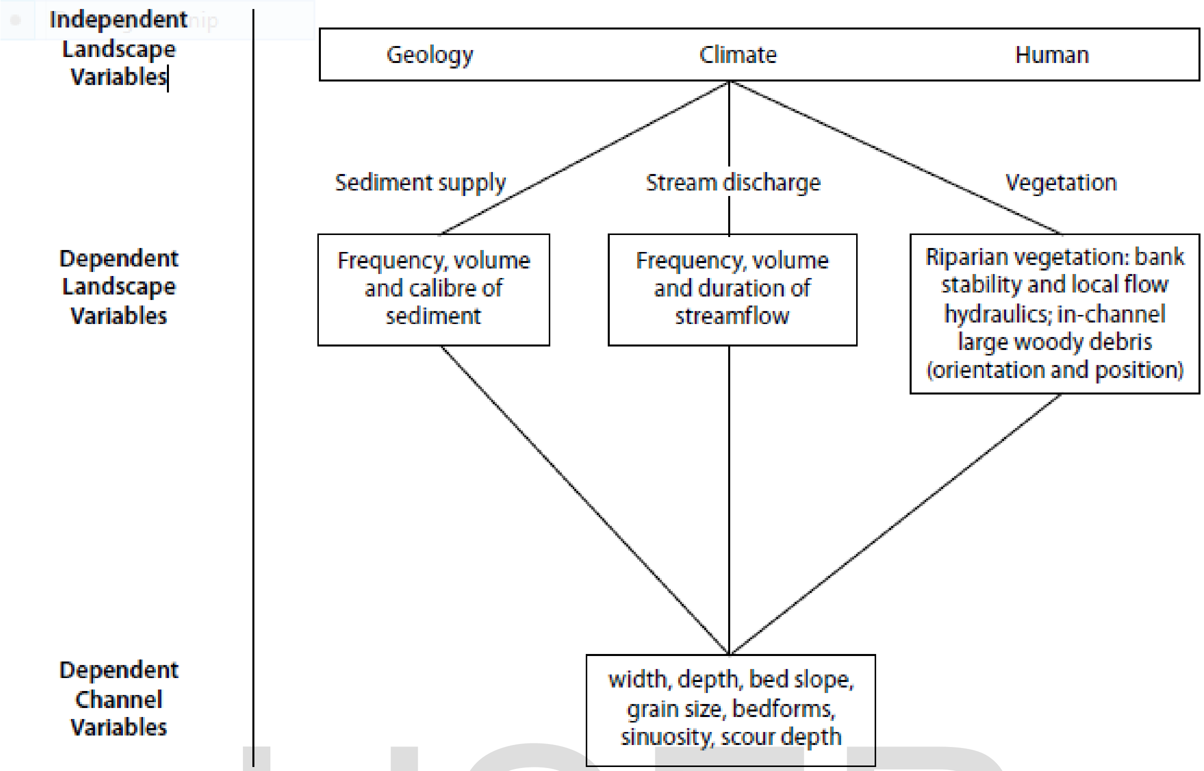

Figure 1. Governing conditions as independent landscape and watershed variables and the dependent channel variables (modified from Montgomery and Buffington 1993; Buffington et al. 2003).

The fluvial dynamics at a given point along a stream can be influenced by the various processes occurring in the watershed upstream. Classical conceptual models depict channel morphology as primarily a function of stream-flow and sediment transport rate, where transport rate equals sediment supply for equilibrium conditions (e.g., Lane 1955; Blench 1957; Schumm 1971). These models fail to clearly address the role of vegetation or other boundary conditions, which often play a critical role in determining channel morphology. This shows that the form of a channel is controlled by driving variables (flow and sediment supply), and boundary conditions (valley slope and confinement, channel substrate and riparian vegetation). This present study considers processes that function at watershed and reach scales. It reviews holistically the channel form processes from the catchment and reach scale perspectives and the channel adjustments they cause or are likely to cause. The fluvial system is affected by changes in the external basin controls. These affect the channel controls, in turn leading to changes in channel form.

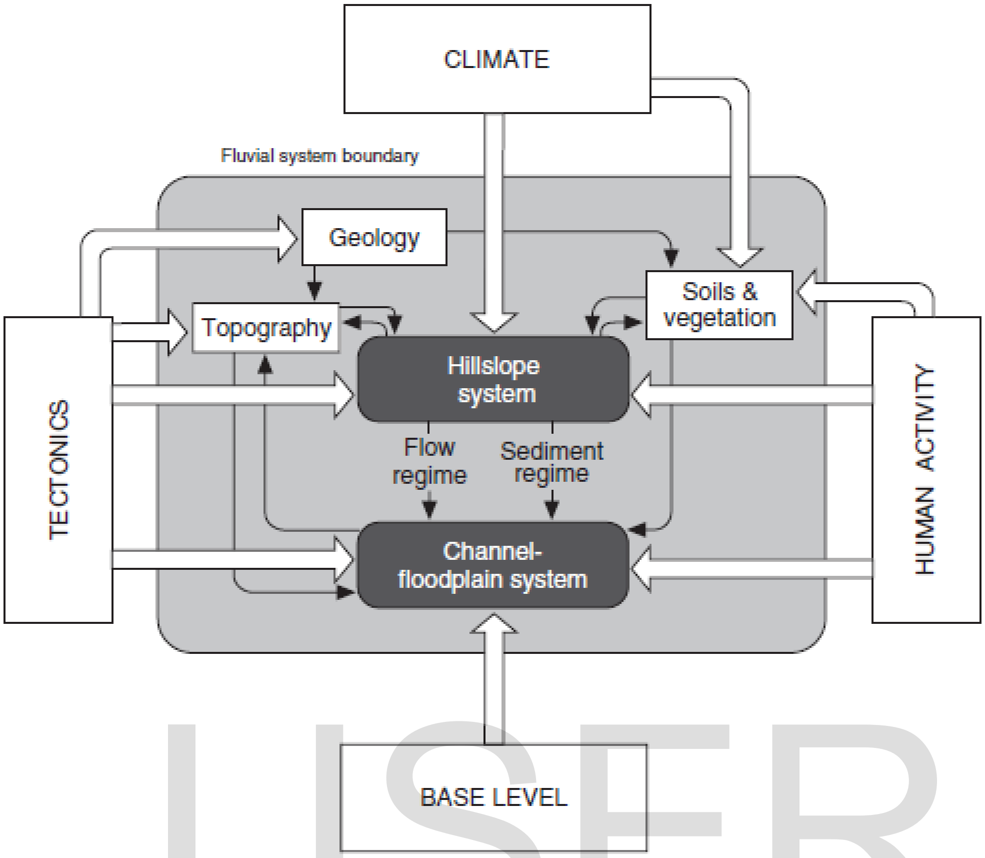

Figure 2 Simplified representation of the fluvial system. (Charlton, 2008, P. 14)

Autogenic Controls/ Processes and Morphologic Changes

According to Charlton, (2008), the form of a channel is controlled by the driving variables (flow and sediment supply), and boundary conditions (valley slope and confinement, channel substrate and riparian vegetation), as seen in Figure 3. The form of a channel is largely a function of the water and sediment supplied to it. Short-term channel adjustments are directly influenced by the flow and sediment regimes. Adjustments to channel form occur as a result of process feedbacks that exist between channel form, flow and sediment transport. At the reach scale, the type of adjustment that can take place is constrained by the valley setting, the nature of bed and bank materials, and bank vegetation. This gives rise to a wide diversity of different channel forms.

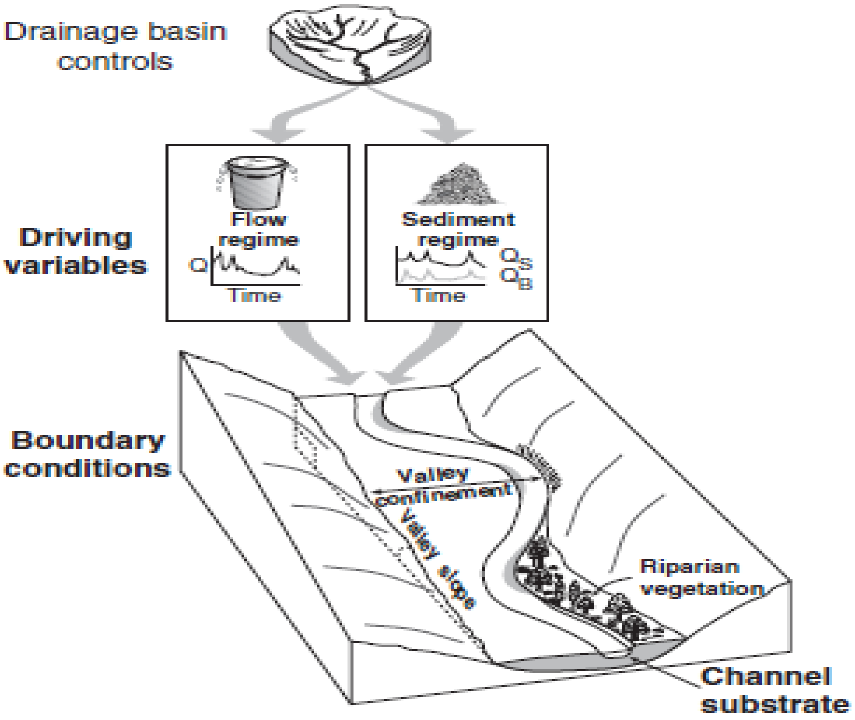

Figure 3 The driving variables and boundary conditions that control the form of a channel reach (Charlton 2008).

Flow Regime (Discharge)

Changes in the magnitude and frequency of channel discharge may result from alteration of either the total precipitation falling on the watershed or changes in run-off production and routing through channel network (Montgomery and Buffington, 1998; Charlton, 2008). The discharge characteristics of a stream channel, the frequency and magnitude of discharge events, and hydraulics of flow (depth and velocity), vary with climate and the scale and slope of the channel and the bed characteristics (Thompson, Ramsey, Molhagen, Evans and Lehman, 1997). Rivers and streams undergo natural short-term variations in hydrology in response to daily, seasonal, or long term variability in precipitation, and also in response to longer term climate cycles. Since discharge influences stream power, velocity and bed shear stress, the characteristics of the flow regime have an important influence on channel form. The flow in river channels exerts hydraulic forces on the boundary (Charlton, 2008). Discharge varies both spatially and temporally in natural river channels, and fluctuates over time in response to inputs of precipitation. Stream discharge includes the frequency, magnitude, and duration of stream flows. Both temporal and spatial variability in discharge can have a large influence on channel morphology (Hogan and Luzi, 2010). The characteristics of the flow regime are determined not only by the climate but also by the physical and land use characteristics of the drainage basin. The bank full discharge is of morphological significance. Land surface modification during urbanization changes the type and magnitude of runoff processes. This increases peak discharges because of increased impervious surfaces. The resultant effects of these changes are channel expansion either by incision or widening. Large impervious surfaces connected to river channels via land drainage or storm sewers can lead to channel expansion. Changes in vegetative cover can affect the flow regime in the stream channels through changes in water yields, either low flows or peak flows. Channels are shaped by a range of flows. The geomorphological effectiveness of a given flood depends not only on its size, but also on the frequency with which it occurs. Channel morphology reflects in part the dominant discharge experienced by a stream, for example the "bank full" discharge or typical mean annual flood discharge, and also the effects of extreme discharge events. (Thompson, et al, 1997). A reduction in stream discharge, or suppression of peak discharges, typically results in aggradation of sediment within the channel and steepening of the channel gradient. This is accompanied by a decrease in width and depth of the channel, as well as braiding and often increased channel vegetation. An increased discharge normally results to incision of the channel, an increase in width of the channel, reduction in channel vegetation, and slope reduction. Increased discharge may result from climate change, or stream capture.

Sediment Regime

Sediment supply varies through time. The volume and the textural characteristics of sediment are very important. Coarse sediments such as gravel and sand are carried in traction or creep along the floor of the channel (bed load), while fine sediments such as silt and clay suspended in the water (suspended load), or a varied proportion of both (mixed load) are carried in suspension (Thompson, et al, 1997). The grain size and sorting of bed load sediment, and the presence and scale of bed waves (ripples, dunes, bars) on the channel floor influence the hydraulic geometry of the stream, and in turn the channel morphology.

Changes in the sediment load will bring about changes in channel morphology. Changes in the volume and size of sediment are brought about by variations in sediment supply from the drainage basin. As with the flow regime, it is the processes in the drainage basin, upstream from a given reach, that influence sediment supply (Charlton, 2008). Channel response to increased sediment supply depends on the ratio of transport capacity to the sediment supply (Montgomery and Buffington, 1998).

Bed load transport capacity is a key determinant of channel form and stability. Any imbalance in the relationship between supply and transport leads to channel instability via erosion or aggradation (Jansen, and Nanson, 2010). An increase in bed load supply, or coarsening of the bed load sediment, where the amount of introduced sediment overwhelms the local transport capacity typically results in aggradation of sediment in the channel, shallowing (decrease in depth) of the channel, channel widening, braiding, and steepening of the channel gradient (Thompson, et al, 1997;. Montgomery and Buffington, 1998). Aggradation can be triggered in several ways, for example where the sediment supply is increased by upstream channel erosion, mass movement, or human activities such as mining. Channels undergoing aggradation have numerous channel bars with expanded shallow channels (Charlton, 2008).

Deposition within the channel may lead to the channel bed becoming elevated above the surface of the floodplain. This, together with reduced channel capacity, increases the incidence of flooding and also promotes channel migration. An increase in sediment load can be encountered in the early construction phases during urbanization of a drainage basin. Conversely when the stream power exceeds what is needed to transport the sediment load through the reach, this excess energy is used to entrain sediment from the channel bed and erode the channel boundary. In this case it is degradation**.** This can be caused by an increase in discharge, possibly as a result of an increase in flood frequency, or by a decrease in sediment supply. It can occur downstream from dams or where gravel/sand mining has removed sediment from the river channel bed. In sinuous channels, increase or decrease in sediment load can result in an increase or decrease in meander wavelength and an increase or decrease in sinuosity respectively (Thompson, et al, 1997).

Valley Slope

Valley slope is related to the volume of stored sediment in the valley, and represents the short- to medium-term maximum possible gradient that a stream channel can attain (Hogan and Luzi, 2010). It refers to the downstream slope of the valley floor but not the slope of the channel itself and determines the overall rate at which potential energy is expended along a given reach (Charlton, 2008). The valley slope on a given channel reach is determined by a combination of factors including tectonics, geology, the location of the reach within the drainage basin and the long-term history of erosion and sedimentation along the valley. The valley slope determines largely the stream power available along a given reach and it is possible for adjustments to occur that increase flow resistance at different scales of channel resistance, form resistance and boundary resistance (Charlton, 2008). Various types of channel and floodplain morphology are associated with low, medium and high-energy environments.

Valley confinement

A channel can be described as confined, partly confined, or unconfined, depending on how close the sides of the valley are. Channel confinement strongly influences channel response (Montgomery and Buffington, 1998). In **confined** settings channel adjustments are controlled by the valley walls, which also increase flow resistance. The degree of slope–channel coupling is influenced by the valley width. Sediment inputs from mass movements and other slope processes may exceed transport capacity, and do influence the channel form. Some degree of lateral migration and floodplain development is possible in partly confined settings. The river is prevented from migrating further, where it comes against the valley wall or hill slope and which can lead to the development of over-deepened sections of channel. The channel is termed unconfined. Unconfined channel possess extensive floodplains across which over bank flows spread which limits the effects of peak discharges on channel morphology. In contrast confined channels efficiently translate high flows into increased basal shear stress (Montgomery and Buffington, 1998). Where the hill slopes are a long way from the channel and have relatively little influence in contributing to the channel load (Charlton, 2008)

Channel substrate

Lots of differences are seen in the form and behavior of channels developed in different substrates and the substrate determines how resistant the channel is to the erosive force of the flow. It also influences boundary roughness, and therefore flow resistance (Charlton, 2008). The character of the bed and bank materials influences the magnitude and rate of change that a stream channel may experience (Thompson, et al, 1997). According to Charlton (2008), alluvial channels formed in sand and gravel are generally more easily adjusted than those with cohesive silt and clay substrates. This is because the individual particles can be entrained at relatively low velocities, so non-cohesive substrates tend to be associated with wider, shallower cross-sections and faster rates of channel migration. Bedrock and mixed bedrock-alluvial channels are influenced over a range of scales by various geological controls. Bedrock incised channels typically will not experience the potential for rapid short-term lateral migration or down-cutting shown by alluvial channels (Thompson, et al, 1997).

Riparian vegetation

Vegetation on the banks and bed of river channels controls channel form in various ways. It gives protection and strength to the banks, and research has shown that a dense network of roots can increase erosion resistance by more than a factor of ten (Charlton 2008). As a result, channels with vegetated banks are often narrower than those with non-vegetated banks under similar formative flows. This effect is most marked for densely vegetated banks (Hey and Thorne, 1986). According to Thompson, et al, (1997) the type and density of vegetation in the channel and banks, and the presence of channel obstructions such as fallen logs and flood debris accumulations influences channel geometry. Vegetation may change in response to natural climate variation, conscious or unconscious introduction of exotic riparian vegetation species, overgrazing, forest cutting or change in land use within a drainage basin (for example an increase in area cultivated, or urbanization).The resultant effect of increase in channel vegetation will typically be sediment aggradation within the channel, channel contraction, and an increase in channel roughness. Conversely, A decrease in channel vegetation often results in down-cutting, channel widening, reduction in bed roughness, increase in sediment yield, and an increase in the rate of lateral channel migration (Thompson, et al, 1997). Flow resistance can also be increased by vegetation growing on the bed and banks, as well as by woody debris (fallen trees and branches) that enters the channel from the banks.

Allogenic Controls/ Processes and Morphologic Changes

The fluvial system is affected by changes in the external basin (catchment) controls. These affect the channel controls, in turn leading to changes in channel form. Changes in the external basin (catchment) controls – primarily climate, geology, tectonics and human activity – affect flow generation and sediment production within the drainage basin (Fig.4). This frequently results in modifications to channel form. We have under autogenic processes looked at how the form of a channel is controlled by driving variables (flow and sediment supply), and boundary conditions (valley slope and confinement, channel substrate and riparian vegetation).Here we will look at the external basin controls. Changes in the external basin controls – primarily climate, geology, tectonics and human activity – bring about longer-term changes. They act as controls on the flow and sediment regimes and, through a complex sequence of adjustments, bring about long-term changes or modifications in channel form and behaviour. The magnitude and availability of sediment supply in rivers is influenced by key catchment controls (Fryirs and Brierley, 2013).

Climate

The amount and duration of precipitation, temperature variability, and seasonality in a drainage basin influence the discharge, nature of vegetation, and sediment character in a stream channel. Rainfall intensity has effects on runoff generation. It can result in flash flood, with high erosive effects on the landscape. Hot weather conditions and prolonged sunshine can influence rock weathering, be it mechanical, chemical or biological. According to Charlton (2008), there have been major shifts in global climate, since the Last Glacial Maximum which have affected river systems worldwide with changes in flow and sediment yields have led to phases of channel alleviation and degradation. There have also been dramatic changes in channel pattern and behaviour. Arid climates tend to result in a high bed load sediment, flashy or ephemeral discharge, sparse vegetation, and braided channel patterns. Humid climates tend to favour high suspended sediment loads, perennial discharge, more vegetation, and meandering channel patterns. A long- term change in climate will set in motion a series of processes that result in a new equilibrium channel morphology (Thompson, et al, 1997).

Tectonics (Geology and topography)

From the geological records, the Earth’s crust has undergone intense deformations by internal forces leading to warping, folding, faulting and tilting which have had a profound effect on river systems globally (Charlton 2008). Long-term, large-scale uplift, subsidence or deformation disrupts channel networks and long profiles. At the reach scale, channel adjustments are associated with changes in slope, lateral tilting and localized faulting. Regions, such as the

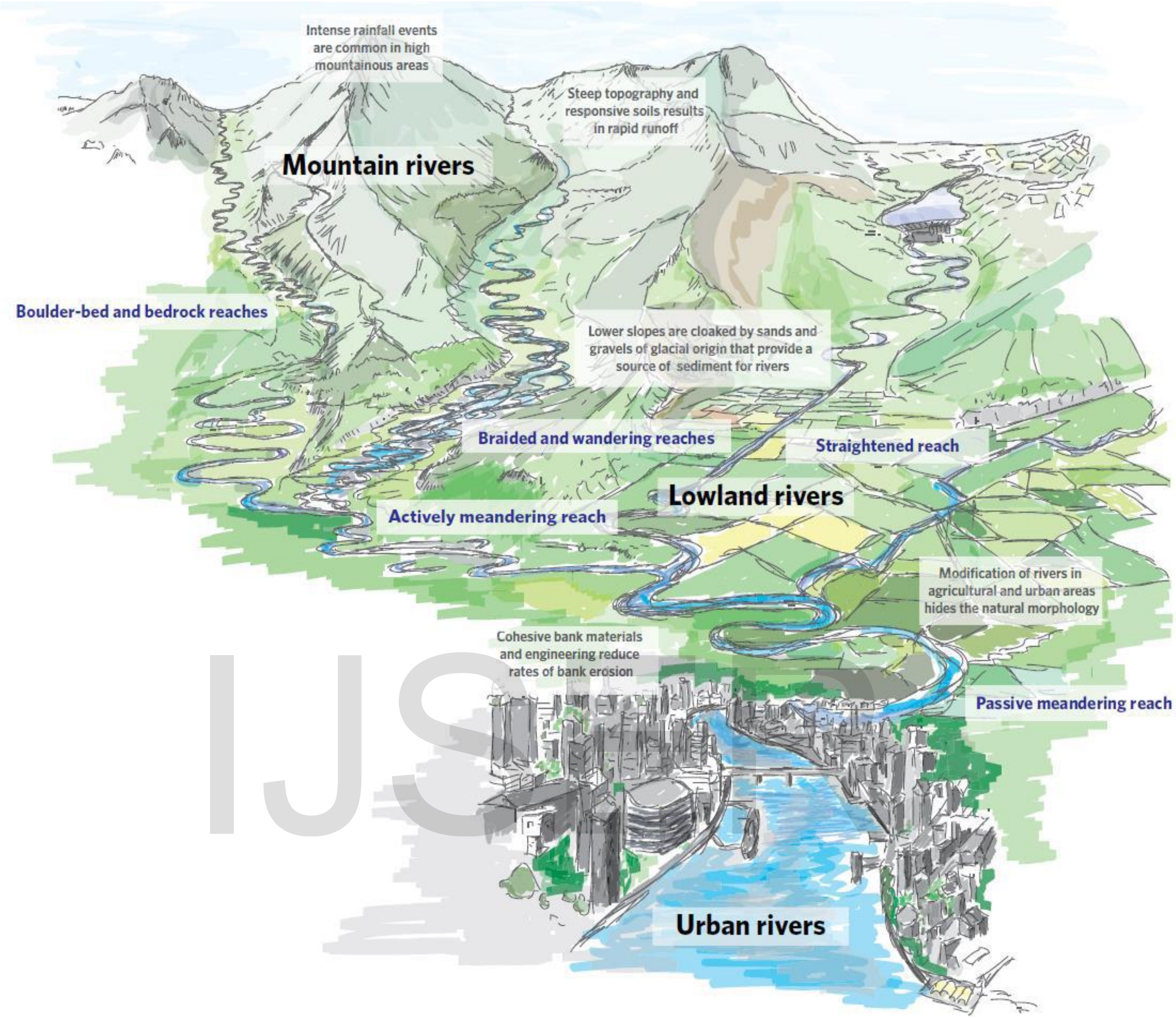

Figure 4. River catchment (After Morreto, 2013)

Himalayas and Andes, which are tectonically active have some of the highest sediment yields in the world (Charlton, 2008).

Rainwater generally runs off rapidly from watersheds with ‘hard-rock’ geologies or areas covered by paved surfaces in urban areas resulting in larger floods for a given rainfall even (Moretto, 2013). The slope of a catchment as determined by its geology and glacial history, together with land cover and land management are the most important factors that control the rate at which water runs off the land. The stream power or energy with which rivers erode, transport and deposit material is determined by the product of stream flow and channel slope.

The surface configuration or topography has strong influences on the availability of sediment for rivers; the lower slopes of many valleys are laden with a mixture of sands and gravels – a by-product of glaciations and these are reworked by rivers to produce distinctive landforms associated with specific channel types (Moretto, 2013). According to Harbor, Schumm, and Harvey, (1994), changes in slope, together with varying rates of sedimentation, have primary influence on the channel pattern. There were significant variations in channel morphology for rivers crossing two uplift domes in the American states of Louisiana and Mississippi (Burnett and Schumm, 1983).

Base-level change

This is the lowest point of a river's course, usually sea level. it marks the level below which a river cannot erode and is one of the external basin controls. Base-level change is caused include by tectonic uplift or subsidence, changes in sea level, isostatic uplift of land masses and human activity such as dam construction. There can be Local base level changes when aggradation or incision in the main channel alters the base level of the tributaries that join it (Charlton, 2008). Changes in the relative rates of eustatic sea level rise and isostatic uplift have resulted in wide variations in base-level change from place to place.

There may be changes in channel gradient over time due to gradual downcutting or aggradation, and in response to change in the base level to which a stream is graded. Hydrologic conditions and the stream sediment transport capacity can be influenced by stream gradient. Hence, a change in gradient will induce change in flow conditions that result in either deposition or erosion of sediment, and in turn changes in channel geometry - width, depth, and pattern (Thompson, et al, 1997).

A rise or drop in base level results in lowering of the channel gradient and propagating upstream aggradation or in steepening of channel slope and propagating upstream degradation. Natural rise in base-level may occur as a result of landslides or otherwise impounding a stream's drainage resulting in lake formation, a rise in sea level, or the migration of trunk stream away from the mouth of its tributary, while a natural fall in base-level of erosion can result from evaporation of a lake, lowering of sea level, or migration of a trunk stream toward the mouth of a tributary (Thompson, et al, 1997). Anthropogenic activities such as lake draining, channel straightening or a meander loop elimination can also give rise to a relative fall in local base-level resulting in local steepening of channel gradient (a "knickpoint") that propagates upstream over time.

Human activity

Human activity has a direct correlation with landuse and landcover. Land use is talking about the use to which a particular piece of land is put by man. The effect of land use on river flow, and the consequent land degradation, is one of the most important environmental problems of our time.

According to Carter (1961), Anderson (1970); Hammer (1972); Odemerho (1992); and Oyegun (1994), urbanization of a drainage basin could significantly affect its hydrology by increasing flood magnitudes and increasing lag times. Progressive urbanization of a drainage basin can result in changes of river channel size and form with time (Leopold & Maddock 1973; Ebisemiju 1976; Slymaker 1993; Oyegun 1994). Gregory and Walling (1971), found out that building construction and related civil engineering works seem to increase sediment generation and yield in a drainage basin. Urbanization has some serious impact on river basin response through variations in sediment yield, bankfull discharge and channel capacity (Mgborukor, 2014). Urbanization of watersheds results in increased stream discharge, flow variability and increased sediment loads leading to habitat degradation (Allan, 2004; Chin, 2006).

The type and density of riparian vegetation (grasses, shrubs or trees) are known to stabilize the river bank and channel (Barasa, et al,. 2015). According to Charlton, (2008), deforestation increases the sensitivity of soils to erosive forces, accelerating erosion and sediment delivery to the channel network. Topsoil removal also exposes the relatively impermeable lower soil layers, thus reducing infiltration rates, enhancing storm runoff and increasing the magnitude of flood peaks. Normally, runoff and sediment yields are relatively high from cultivated and intensively grazed land, when compared with forested areas. Runoff is positively influenced by impermeable surfaces, such as roof tops, paved areas, roads and car parks. Land drainages and sewers also act as conveyors, transmitters of running water to river channels.

The construction and operation of dams alters both flow and sediment regimes. Flow regulation often reduces flood peaks, and modifies the seasonal distribution of flows. Dams also act as barriers to sediment transport, which in turn affects channel form. Upstream, where the river flows into the reservoir, the loss of competence means that all the bedload is deposited. Over time, this leads to the buildup of a wedge of sediment. Downstream you have massive incision and sediment starved hungry waters as a result of the dam in place. The sediment-starved flow downstream from dams is described as 'hungry water'. The absence of a sediment load during high flow releases results in an energy excess. If the resistance of the channel substrate, is less than the energy, bed erosion and channel incision will occur Most of the fine material carried in suspension is trapped when it settles out in the still waters of the reservoir. According to Williams and Wolman, 1984, these losses can account for up to 99 per cent of the suspended load in large reservoirs.

Conclusion

Streams change in shape or position over time in response to a variety of interrelated variables. Over geologic time channels respond to tectonic uplift, erosion of the landscape, and climate change and over historic time channels respond to changes in discharge and sediment supply from both land use and such extreme events as floods and droughts (Montgomery and Buffinghton, 1993). There is a general sequence of channel adjustments following natural or anthropogenic disturbances that cause streams to have more energy and erode more sediment.

Rivers and streams shape and reform their channels through erosion of the channel boundary (bed and banks) and the reworking and deposition of sediments. Erosion and undermining of the banks can lead to channel widening. Scouring of the channel leads to channel bed incision, while sediment deposition leads reduction of the channel depth and to the formation of channel bars (Charlton, 2008). The form of a channel is controlled by driving variables (flow and sediment supply), and boundary conditions (valley slope and confinement, channel substrate and riparian vegetation). Changes in the external controlling variables-climate, human activity, tectonics and base level influence the whole fluvial system.

In this paper we reviewed the autogenic and allogenic processes that are responsible for channel morphologic change. Knowledge and understanding of the catchment scale and reach scale processes that influence channel morphology is very significant in the evaluation of stream ecosystem and aquatic habitats. The textural characteristic of the sediment is very paramount in the determination of spawning habitats for the fish species. Gravel bed substrate make an excellent site for spawning and fine sediment seems to clog the pore spaces in the coarse bed forms. Channel forms and processes, an important aspect of Fluvial geomorphology should be seriously taken into account for sustainable river ecosystem management.

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