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Climate Change and its Impact on Catchment Linkage and Connectivity

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Abstract

Geomorphic connectivity among different landscape compartments is a result of physical linkage and material flux exchange. Physical linkage is the structural component, and material flux is the functional component of connectivity. Both components are interlinked and define catchments processes and responses. Terrain characteristics such as slope and topography control define structural connectivity, whereas functional connectivity is defined by processes and stimuli such as rainfall events, land cover dynamics, and tectonics. There exists feedback between structural and functional connectivity, and they actively modify each other to keep the geomorphic system in an equilibrium state. Under the climate change scenario, dynamics of the processes such as rainfall and land cover are changing rapidly, which in turn affects the catchment connectivity and linkages. The present study first introduces the concept of geomorphic connectivity in a comprehensive manner and then discusses the impact of climate change on catchment structures and processes in a theoretical framework.

Keywords

Hydro-geomorphic connectivity · Catchment processes · Floodplain-channel connectivity · Hill slope-channel connectivity · Climate change · Connectivity

8.1 Introduction

Among all environmental externalities, global warming is the most prominent one, making climate change the ultimate challenge for world economies (Nordhaus 2019). Climate change at a historical time scale is manifested in several extreme events the frequency of which is expected to increase even further (IPCC 2014). The impact of climate change on the basin linkage and connectivity and ultimately on sediment and hydrological connectivity depends on individual basin characteristics. Usually, topographic factors such as catchment morphometry and catchment land-cover types are the first-order controls that characterize the period and magnitude of the runoffs, and sediment generation and transportation. Therefore, to understand the impact of climate change on catchment linkage and connectivity, it is important to understand how connectivity-defining factors are being modified by climate change.

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Two major factors that impact the catchment processes and hence connectivity at various scales are land-use change and climate change (Wada et al. 2011; Sinha et al. 2020). Land-use patterns can also get altered by climate change (Sinha et al. 2020) which may imply further alterations in the catchment processes such as evapotranspiration, soil erosion, and runoff generation (Chawla and Mujumdar 2015; Bussi et al. 2016; Op de Hipt et al. 2019; Sinha et al. 2020), amplifying the impact of climate change. For example, a study in the Willamette River Basin, Oregon, USA reported that the regional climate could be significantly warmer in the twenty-first century which might potentially change the dominant vegetation cover type of the basin (Turner et al. 2015). This study predicted that the currently present needle leaf type forest would convert into a mixture of needle leaf and broad leaf type forest. Moreover, the forest might get fragmented. Such climate change-induced alterations in the forest cover type may radically modify the hydrological cycle of the basin (Turner et al. 2015) and the hydrological connectivity.

In various studies involving a comparison between climate change and land-use land-cover (LULC) change as the major control on catchment processes, the impact of climate change is found to be much more significant than the LULC change. For example, Kim et al. (2013) studied the impact of LULC and climate change on the streamflow in the Hoeya River Basin of South Korea. They concluded that among LULC change and climate change, the former has less impact on the stream flows than the latter. However, the impact of LULC change was also significant on the streamflow. Similarly, in Be River catchment of Vietnam, the influence of climate change was observed to be stronger than the influence of LULC change on the hydrological processes (Khoi and Suetsugi 2014).

The present chapter first discusses the concept of connectivity in hydro-geomorphic systems and then presents the ways in which various elements of hydro-geomorphic connectivity are getting impacted by climate change. In particular, possible impacts of climate change on hydrological connectivity and sediment connectivity have been discussed in detail.

8.2 Concept of Connectivity in Hydro-geomorphic Systems

In hydro-geomorphic systems, connectivity is defined as “the efficiency of transfer of materials between system components” (Wohl et al. 2019, pp. 2). Here, water, nutrients, and sediments are materials in the geomorphic system. The catchments, sub-catchments, water bodies, etc. are system components or landscape units. The presence or absence of linkage (or, connections) among different system components defines the degree of interaction (e.g., streamflow rates, sedimentation, ecological functions) in the system (Singh et al. 2021). Further, such connections vary in space and time (Harvey 2002), rendering connectivity to a spatio-temporal dynamic phenomenon.

In hydro-geomorphic systems, there are three types of connectivity i.e. landscape connectivity, hydrological connectivity, and sediment connectivity (Wohl et al. 2019). Further, there are two components—structural and functional connectivity, inherent to all three types of hydro-geomorphic connectivity (Turnbull et al. 2008; Wainwright et al. 2011). All types of hydro-geomorphic connectivity operate in four dimensions: three spatial (longitudinal, lateral, vertical) and one temporal dimension (Ward 1989; Jain and Tandon 2010). Because of its multi-dimensional property, connectivity can be used to understand the inter-and intra-scale hydro-geomorphic (e.g., sediment transport) processes (Bracken et al. 2015). Hydro-geomorphic connectivity gets actively and significantly altered by various anthropogenic factors such as drainage reorganization, land-cover changes, topography alterations (Pringle 2003; Hooke 2006; Fryirs 2013; Singh et al. 2017; Singh and Sinha 2019). Recently, the connectivity concept has been used to evaluate the impacts of climate and land-use change on the navigation of sediments (López-Vicente et al. 2013; Lane et al. 2017) and water

(Smith et al. 2010) within and among various geomorphic units. Therefore, climate change phenomena can impact hydro-geomorphic connectivity in a major way. However, before understanding such impacts and possible measures to minimize them, it is necessary to understand the hydro-geomorphic connectivity and its elements.

Various researchers have used the connectivity concept to understand and evaluate hydrological and sedimentary processes (Brierley et al. 2006, Turnbull et al. 2008, Lexartza-Artza and Wainwright 2011, Jain et al. 2012, Fryirs and Gore 2013, Gomez-Velez and Harvey 2014, Bracken et al. 2015, Lisenby and Fryirs 2017) at different scales and settings. A recent and comprehensive study by Singh et al. (2021) defined a connectivity framework consisting of three basic elements of geomorphic connectivity—connectivity types, connectivity components, and connectivity dimensions (Fig. 8.1). This framework presents the interrelationships and feedbacks among different connectivity elements.

"Hydrologic connectivity is the water-mediated transport of matter, energy, and organisms within or between elements of the hydrologic cycle" (Freeman et al. 2007, p. 1). Further, "the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape" (Bracken et al. 2015, p. 177) is defined as sediment connectivity. Recently, Heckmann et al. (2018) presented a working definition of connectivity by encapsulating both sediment and hydrological connectivity: "…we define hydrological and sediment connectivity as the degree to which a system facilitates the transfer of water and sediment through itself, through coupling relationships between its components. In this view, connectivity becomes an emergent property of the system state, reflecting the continuity and strength of runoff and sediment pathways at a given point in time" (Heckmann et al. 2018, pp. 3). Although water and sediment can freely navigate from one

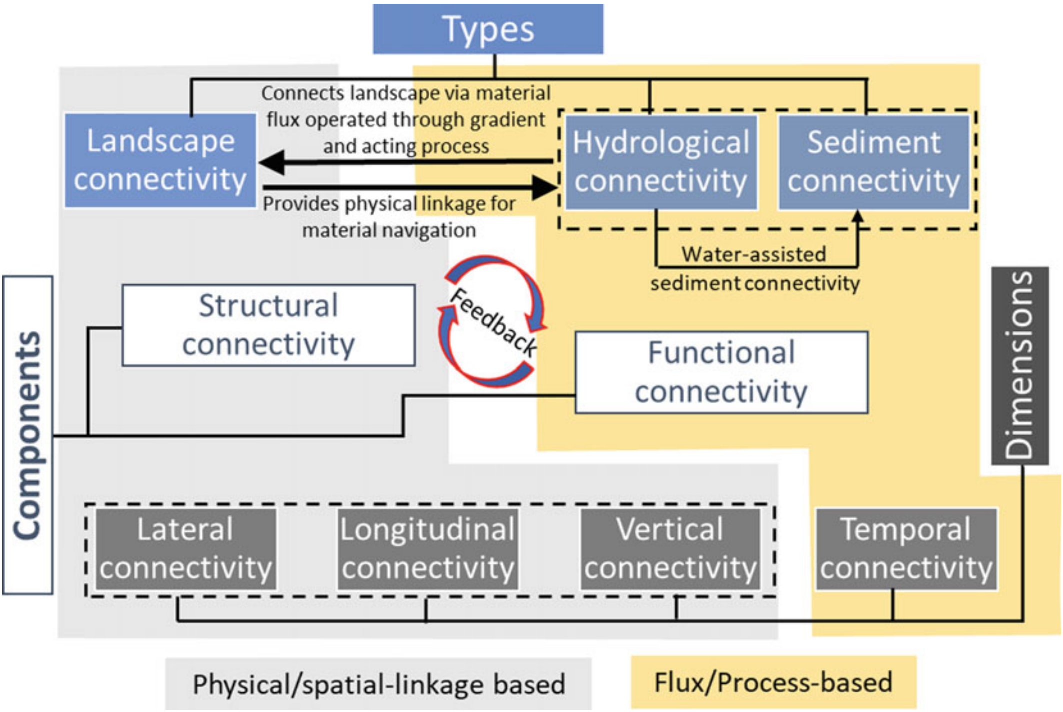

Fig. 8.1 The connectivity framework. Modified after Singh et al. (2021)

landscape to other, the landscapes themselves are static features and they get connected only because of the exchange of water and sediment (Singh et al. 2021). Hence, sediment and hydrological connectivity are the main drivers of landscape connectivity. Further, in many cases, sediment transport is strictly water-controlled and in such scenarios, hydrological connectivity can act as a proxy for sediment connectivity as well. Therefore, in such cases, just by evaluating hydrological connectivity, the other two hydro-geomorphic connectivity can be easily comprehended.

All types of hydro-geomorphic connectivity have two components—structural and functional. The spatial patterns (Turnbull et al. 2008) and physical linkages present at various scales in landscape units define the structural component (Keesstra et al. 2018; Turnbull et al. 2018). Therefore, catchment linkage is the structural component of catchment connectivity. Channel network and Hydrological Response Units (HRUs) are typical examples of structural components. The functional component is the result of the interaction between the structural components and acting processes (Turnbull et al. 2008; Wainwright et al. 2011; Bracken et al. 2015). Sediment and water discharge are typical examples of the functional component of hydro-geomorphic connectivity. On temporal scales, the structural component gets modified by the functional component, thereby, forming a feedback system between these two components (Singh et al. 2021).

Hydro-geomorphic connectivity operates on four dimensions comprising three spatial dimensions i.e. lateral, longitudinal, vertical, and one temporal dimension (Ward 1989; Jain and Tandon 2010). However, all three spatial dimensions are interrelated, and they follow a conservation law, i.e., overall connectivity among different spatial dimensions at a given place remains the same and the connectivity increment in one dimension is a result of connectivity decrement in some other dimension at that place. For example, poor vertical connectivity (percolation) results in runoff generation (strong horizontal connectivity). At a large scale, a decrease in one dimension of connectivity can translate into a decrease in another dimension. For example, reduced vertical connectivity in the floodplain can result in reduced base flow to the channel and therefore, reduced lateral connectivity between floodplain and channel. Further, a reduced lateral hydrological connectivity might result in a reduction of the channel’s longitudinal hydrological connectivity. All connectivity types, components, and spatial dimensions also vary with time, and this defines temporal connectivity. The temporal dimension of connectivity induces dynamics in hydro-geomorphic connectivity, i.e., connectivity changes with time. This is where climate change issues become important, and therefore, a conceptual understanding of the impacts of climate change on hydro-geomorphic connectivity needs to be developed.

8.3 Climate Change and Connectivity

Different elements of connectivity are expected to get impacted differently because of climate change. For example, many times, the impact of climate change on hydrological connectivity and sediment connectivity might not be equal. For example, Azari et al. (2016) constructed three climate change scenarios in Northern Iran and found that for the years 2040–2069, stream flows will increase to 5.8%, 2.5%, and 9.5% annually, whereas the sediment yield will increase to 47.7%, 44.5%, and 35.9% respectively. Similar results were observed in Be River catchment of Vietnam where due to climate change, annual streamflow increased by 26.3%, and sediment load by 31.7% (Khoi and Suetsugi 2014). In Northern Iran, a disproportionately higher increment in sediment load than the streamflow was attributed to the power function relationship between streamflow and sediment yield (Azari et al. 2016). Consequently, the impact of frequent and large-intensity floods in northern Iran would result in greater sediment yield than the streamflow. In the case of Vietnam, the disparity among streamflow and sediment yield could be related to the conversion of forest covers into agricultural lands (Khoi and Suetsugi 2014).

Depending upon the present and future conditions and geographical locations, some elements of connectivity can be negatively impacted, and others can be positively impacted. Further, the impact of climate change might not be unidirectional and static. Different regions of the Earth might observe the dynamic impacts of climate change in different periods. For example, a study on the Nile River Basin investigating the impacts of climate change under 2007 IPCC scenarios and found that in the early twenty-first century, due to increased precipitation, the Nile River might observe increased flows, but in the mid- and late twenty-first century, the river might observe decrement in the streamflow induced by a decline in precipitation and increased evaporation (Beyene et al. 2010).

Structural properties of a landscape (i.e., structural connectivity) and dynamics of hydrometeorological processes (such as duration-intensity-frequency of rainfall) control the landscape response and hence, the functional connectivity (Singh et al. 2021). Climate variabilities are expected to translate into extreme river flows and thereby, increased flood risks (Fang et al. 2018). An alteration in structural component influences the functional component (Vanacker et al. 2005; Turnbull et al. 2008; Wainwright et al. 2011; Bracken et al. 2015; Singh and Sinha 2019). Therefore, feedback exists between structural and functional components of hydrogeomorphic connectivity (Fig. 8.2). This feedback is controlled by various terrain and process parameters. It has been demonstrated that any alteration in the spatial pattern of land use in catchments results in a variation in the functional component of connectivity (Vanacker et al. 2005; Singh et al. 2021). Climatic conditions also strongly control the structural connectivity. For example, increasing rainfall usually positively correlates with an increase in vegetation (Jordan et al. 2014). An increased vegetation cover enhances the impedance to the surface water flows, thereby, decreasing the functional connectivity (Singh and Sinha 2019). Such impacts of vegetation cover are more pronounced in catchments with flat terrain. Changing climate can also impact the structural and functional connectivity at a very large scale. For example, the Ganga plains are characterized by two geomorphologically distinctive systems, East Ganga Plains (EGP) and West Ganga Plains (WGP). The EGP is drained by rivers with high sediment flux and low stream power systems, whereas the rivers draining the WGP show high stream power and low sediment flux systems (Roy and Sinha 2017, 2018). Accordingly, an incised topography is a characteristic of WGP, whereas aggradational landforms are the distinctive features of the EGP. In event of climate change, the differential sensitivity of these two distinctive systems is likely to change the stream power and sediment flux relationships, resulting in severe catastrophes.

In the temporal domain, the impact of the functional component on the structural component has been documented. For example, in the case of sediment connectivity, sediment flux is known to modify the morphology of landscapes (Bracken et al. 2015). Such modifications change the structural framework, and ultimately the physical linkage of the landscapes (Turnbull et al. 2008; Bracken et al. 2013). In the following sections, the impact of climate change on the two most important catchment connectivity i.e., hydrological connectivity and sediment connectivity has been discussed in detail.

8.3.1 Impact on Hydrological Connectivity

The impact of climate change on the streamflow and therefore, the hydrological connectivity of basins has been an area of active research (e.g., Arnell 1999; Mimikou et al. 1999; Middelkoop et al. 2001; Chang et al. 2002; Smith et al. 2010, 2013). These studies indicate that there is a conclusive correlation between climate change and variability in stream flows. For example, Arnell (1999), Middelkoop et al. (2001), and Chang et al. (2002) predicted that the regional hydrology of the snow-dominated regions will

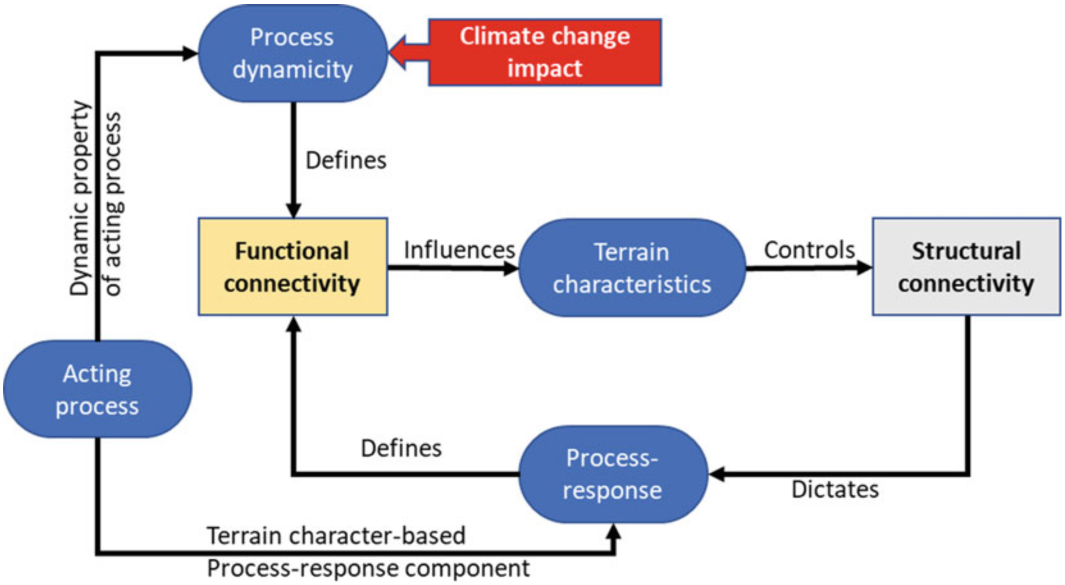

Fig. 8.2 Feedbacks among structural and functional components of hydro-geomorphic connectivity and their controls. Climate change is expected to impact the process dynamics (e.g., rainfall variabilities). Modified after Singh et al. (2021)

observe significant variations under global warming scenarios and the month of maximum runoff are expected to shift. Since hydrological connectivity is expected to be conclusively impacted by climate change, this connectivity can effectively be used to evaluate the climate change-induced modifications to the material fluxes at the catchment scale (Smith et al. 2010). The dynamic aspect of hydrological connectivity is controlled by factors such as "rainfall characteristics, flow path length, and integration, the spatial distribution of areas of low/high abstraction potential and the routing velocity of overland flows" (Smith et al. 2010). It is important to understand how each of such factors will be influenced by climate change and to what degree. The spatio-temporal variations of precipitation (Wainwright and Parsons 2002) and intensity-duration-amount (Bracken et al. 2008) are defining factors of hydrological connections (Smith et al. 2010). Understanding such factors is even more crucial for large and highly populated basins such as Ganga in which monsoonal discharge is expected to increase under climate change scenarios (Whitehead et al. 2018).

A case study by Molina-Navarro et al. (2016) on the Guadalupe River basin, Mexico presents the potential drastic impacts of climate change on basin hydrology which will ultimately impact the basin-scale hydrological connectivity severely. Based on short (2010–2039) and long term (2070–2099) climate change simulations, the authors concluded that the Guadalupe River basin might observe around 45% reduction in runoff in the short-term, and up to 60% reduction in the long-term. Decreased precipitation and increased evapotranspiration are the main factors behind such reductions. Further, it is expected that the aquifer recharge can decrease up to −74%, which will drastically alter the flow of groundwater as well as the base flows.

In regions with large negative water budgets such as the semiarid regions of the world, subsurface flows are typically non-existent and overland flows dominate the outflows (Smith et al. 2010). Even the overland flows generate isolated patches with the occasional connection among such patches (Smith et al. 2010). Such regions are most prone to the changing climate because a reduction in precipitation will diminish the connectivity among the isolated patches even further. Also, an increase in precipitation will impact the region negatively by the generation of flood events. This is because of a sudden increase of connectivity in the horizontal domain without any change in the vertical domain since vertical connectivity such as percolation is a function of lithology which is unlikely to change in pace with precipitation change.

8.3.2 Impact on Sediment Connectivity

Sediment transport and soil erosion processes are expected to be significantly influenced by climate change (Bussi et al. 2016). For example, a study by Jordan et al. (2014) showed that higher rainfall translated into higher total suspended solid (TSS) contribution to surface water systems. The major climate-related stressors that are expected to impact catchment scale sedimentation processes are changes in temperature and precipitation and their subsequent impacts on the vegetation cover and land use (Nearing et al. 2004). These stressors can potentially impact sediment connectivity by altering sediment production and sediment transport (Mullan et al. 2012). For example, a study on the Ganga River estimated that in comparison to the present scenario, the sediment load in this river might increase by 10–40% by mid-century and by 35–79% by the end of the century under changing climate scenarios (Khan et al. 2018).

Extreme precipitation and river discharge strongly control the sediment transportation and hence sediment connectivity within and in-between landscapes. For example, sediment transport in many catchments in Himalayas depends on the precipitation intensity, which in turn dictates the channel morphology and processes. Several Himalayan rivers such as Kosi are highly avulsive (Sinha et al. 2013, 2014) and the high rate of sediment production in its catchment is one of the primary causal factors for its avulsive nature. Climate change may have very significant implications in river basins such as the Kosi draining through Nepal and India where significant spatial variability in sediment connectivity across the basin has been noted; it has also been demonstrated that sediment flux in different sub-basins is controlled by variable slope distribution and land-use/land-cover that are strongly related to the structural connectivity (Mishra et al. 2019). Excessive siltation forms a central problem in the Kosi basin, and it is necessary to understand the implications of siltation on river processes and associated flood risk under climate change scenarios; this would require a comprehensive analysis of sediment connectivity under a modified hydrological regime induced by climate change. This should then lead to developing effective sediment management plans for protection of infrastructure and human lives not just in the Kosi basin but in several other basins across the world.

In addition to the natural hazards, high sediment flux because of modified sediment connectivity is likely to impact the hydroelectric power projects in several basins in a major way. The designed power production capacity of the hydroelectric power plants depends on the discharge of the river and the head at the turbine. The extent of erosion and deposition will change because of spatio-temporal variability in meteorological conditions, and to the hydrological and geomorphological characteristics of the basin. Landslides triggered by hillslope erosion, levee breach, and channel avulsion may result in partial or total abandonment of hydroelectric projects. A recent example is a major landslide in the upstream reaches of the Bhote Koshi (Jure landslide in 2014); this created a large dam upstream, and a small hydroelectric power station downstream became defunct. Further, sediment-extruding mechanisms may be required during higher sediment transport so that the channel is not filled, and sediment does not enter the turbine partially or fully.

In catchments where water-assisted transportation is the prime mode of sediment transfer, sediment connectivity will also decrease with the decrease in hydrological connectivity. However, in arid regions, where eolian transportation is the dominant process of sediment connectivity, a decrease in precipitation will result in higher entrainment of eolian dust (Reynolds et al. 2007) and will enhance sediment transportation. Therefore, the sensitivity of sedimentary processes to climate change is a function of two factors—sediment supply and transport capacity (East and Sankey 2020). In a supply-limited system, a momentary sedimentary response might be observed to an acting forcing, i.e., increased storm activity. Once the supply gets exhausted, the sedimentary response will cease to exist unless more sediments are produced due to weathering (Heimsath et al. 2012).

Perhaps the impact of climate change on the sediment connectivity of a catchment can be best understood in a glacial system. Due to global warming, the glaciers are receding, resulting in an increased extent of paraglacial zones in glaciated regions of catchments (Lane et al. 2017). It is expected that in such events of glacial recession, sediment connectivity will increase in paraglacial regions. This is because (a) deglaciation will expose the underlying sediment, increasing the probability of connectivity between such sediments and stream channels, (b) deglaciation of hillslopes will significantly increase the hillslope-channel connectivity, (c) stream-based sediment transport is faster than glacier-based sediment transport (Lane et al. 2017), (d) lateral migration is easier in proglacial streams than the sub-glacial stream, and therefore, former can gather more sediment than the latter, and (d) glacial debuttressing of valley sidewalls will result into a decrease in the base level of upstream catchments of such valleys—leading to headward erosion in sidewall tributaries (Schiefer and Gilbert 2007). In such deglaciated catchments, with high upslope and downslope sediment connectivity, and increased sediment supply can change the structural connectivity by transforming the river channels to braided systems (East and Sankey 2020). To propagate the impact of climate change-induced deglaciation downstream, a continuous sediment supply will be required. With the cessation of sediment supply, the propagation of climate change response, e.g., braiding of river channel will also cease. Therefore, it could be interesting to evaluate the sensitivity of propagation of climate change impacts in such deglaciated catchment systems.

Recently, a method has been proposed by Zanandrea et al. (2021) to estimate the hydro-sedimentological connectivity index (IHC) of basins as a factor of topography, surface roughness, precipitation, and runoff. It is an enhanced version of the original IC method proposed by Borselli et al. (2008) and Cavalli et al. (2013). The inclusion of precipitation and runoff factors in this method renders it best suitable for the estimation of hydro-geomorphic connectivity under changing climate scenarios. The impact of LULC change can also be implemented in this method by replacing the terrain-derived surface roughness factor with NDVI derived C-factor previously implemented by Singh et al. (2017) and Singh and Sinha (2019). The IHC can estimate both, sediment as well as hydrological connectivity of catchments.

8.4 Conclusions and Outlook

The gravity of the effects of global warming and hence the climate change on the ecology and economy must be realized by humans across the world (Nordhaus 2019). There are a number of factors on which climate change vulnerabilities depend, and such factors vary among communities and places (Panthi et al. 2016). Because of climate change, the water security of the world is under threat (Ravazzani et al. 2015). Therefore, the impact of climate change and global warming on the available water resources for human consumption and for ecological services should always be considered in any water resource management work (Qi et al. 2009), especially since climate change affects every aspect of the hydrological cycle and can potentially affect the water resources by inducing changes in water quantity, subjecting water resources to extreme events, changing water quality. Various aspects of hydrological processes such as peak flow and runoff amount (Prowse et al. 2006), humidity and precipitation (Wang et al. 2008) might get actively altered by climate change.

While it is certain that water resources in basins across the world are going to be impacted by climate change, there are possibilities to mitigate these measures. This can be done by identifying the manageable and unmanageable stressors of water resources (climate change is one of the unmanageable stressors) and trying to reduce the impact of the unmanageable stressors by adjusting the manageable stressors. For example, in the Seyhan River Basin of Turkey, it was found that if water demands can be kept in check, the climate change-induced water scarcity can be mitigated efficiently (Fujihara et al. 2008).

It has been observed that the temporal variabilities in the intensities of precipitation are necessary to understand catchment responses and hydrological connectivity (Wainwright and Parsons 2002; Smith et al. 2010). Therefore, better forecasting of future climate can account for the probable changes in connectivity at catchment scales. An understanding of how different elements of connectivity will get impacted by changing climate can be utilized to mitigate the adverse impacts of climate change.

Understanding the impact of climate change on the catchment linkage and connectivity is most crucial for countries such as India which hosts very diverse geomorphic systems. Various basin-scale projects such as river linking projects and inland waterways projects have been planned in India. The river linkage project is expected to mitigate the flood-drought duality of the country (Misra et al. 2007; Shah and Amarasinghe 2016; Higgins et al. 2018). For such colossal undertakings, the assessment of the catchment response under changing climate is a challenge and should not be ignored.

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