Why are the builders and operators of dams and hydels in the Hindu Kush–Karakoram–Himalaya so poorly prepared for hydroclimatic hazards?

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The large and apparently increasing magnitude of losses of lives and property due to hydroclimatic hazards in the Hindu Kush–Karakoram–Himalaya (HKH), exemplified by the recent February, 2021 Rishiganga and 2013 Kedarnath floods, shows that risk assessment and planning are inadequate. In the Anthropocene, where climate change is a real and present danger, the frequency of such events is likely to increase along with the damage. Based on our present understanding of the hydroclimatic risks in the HKH, we appeal for a more comprehensive plan for improving our understanding and monitoring. The scheme suggests expansion of mapping and assessment of the factors that contribute to risk. Further development of the archives of extreme events as one of the basis for risk assessment, developing real time monitoring of hazard elements such as the potential for lake outbursts and landslides is essential. Artificial intelligence (AI) should be employed to provide early warning. In India a taskforce of the earth scientists, hydrologists, historians and engineers (civil and AI) should be established to chart a course for the creation of this understanding and monitoring. Similar action may be taken up in other HKH countries.

Keywords: Hindu Kush–Karakoram–Himalaya, hydroclimatic hazards, risk assessment, monitoring.

THE 2013 Kedarnath flood, landslide and debris flow disaster and the recent landslide and glacier-modulated flood and debris flow in the Rishiganga[1–3], both in Uttarakhand, India, have caused several deaths and damage to dams and hydel infrastructure. Other examples include floods and debris flows in Ladakh in 2010 and the 2014 floods in Kashmir[4]. There are many such examples across the Hindu Kush–Karakoram–Himalaya (HKH)[5]. These will probably increase in frequency and magnitude as climate warming continues, glacial ice and permafrost melt, and rainfall intensity increases[6,7].

The identification of the Anthropocene – the current period, when the impact of humans on nature is equivalent to many of nature's forces, has '...dethroned humans from a position of claimed supremacy...'[8]. One implication of the Anthropocene events is that the human exceptionalism has been challenged, and this should have elicited greater humility in the face of nature's forces. But in the HKH region, the opposite appears to be happening. Hubris dominates over humility. Here we provide insights from a geoscience perspective on what may be going wrong and give a few suggestions for developing a HKH-centric research and observation policy that can help avert such damages in the future.

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The standard hazard risk assessment method

The combination of landslide lake and glacial lake outburst floods (LLOFs and GLOFs respectively), rainfall-induced floods, and the landslides that melt glacial ice and produce a flood and debris flow as in the Rishiganga, constitutes a complex set of hazards that are difficult, if not impossible to predict. This is also the case in many other much less complex landscapes in the world, where the prediction of a flood using rainfall inputs to a hydrologic model, while possible, is data-intensive, expensive and often inaccurate[4]. The standard method of flood hazard 'anticipation' is probabilistic and relies upon many decades of gauged flood records and observations of landslides and debris flows. From these records, probabilities of extremes well beyond those captured in the records are estimated, with considerable uncertainties. For example, a 29-year dataset of peak flow data for the Kosi river in Uttarakhand was used to calculate return periods up to the 1000-year peak flow[9], with estimates varying by a factor of 5.5 between different probability fits.

In general, this is a highly doubtful method[10], because the records are usually too short for the fitting of robust statistical distributions, the series are usually non-stationary[11] and thus violate one of the assumptions of the method, and the causes of the events are not always the same and often are unknown, once again violating an assumption of the method. Furthermore, analysis of long rainfall records, which exist in the HKH[12], cannot easily be translated into flood records, because of topographic and process complexities and non-linearities between rainfall and stream flow. The method is moot in the Himalaya for another reason, namely there are almost no gauged flood records[9], except for an exemplary record of 85 years of data for the Sharda river in the Indo-western Nepal border. Only a few records of landslides[5] and debris flows are available. Other methods, such as the use of palaeo flood deposits[13,14], or information gathered from the local people memory and ancient texts/chronicles (i.e. social archives), where they exist, are required to supplement the existing gauged records or provide information where gauging has not been carried out. An example of the use of historical records is available from Kashmir[15].

Probability vs possibility

There is a growing body of opinion that probabilistic estimates of extreme events in many domains (including floods, landslides, financial excursions) are of little value, for the reasons mentioned above, even when there are measured records of several decades. The extremes described as black swans[16] (unpredictable events) and dragon kings[17] (events with magnitudes well beyond the described extreme values and which may be to some degree predictable) are more important than the extremes extrapolated from a probability distribution that is based on measured records. This is because the events may be larger and more destructive as they do not conform to the upper tail of a distribution. So, instead of probabilities we have 'stories' in a world of radical uncertainty[18], to use the term employed by two eminent economists Kay and King[19] while writing about decision-making 'beyond the numbers', which describe our attempts to understand the future as '…craving certainties which cannot exist and invent knowledge we cannot have'[20].

We do have historical accounts that provide evidence that very large events have occurred in the HKH and there is no reason to doubt that they will not occur again, based on process understanding. Referring to Woo and Johnson[21], and inspired by statistical physics, it is observed that past sequences of events can 'fill gaps in knowledge of rare events without waiting for an inordinately long time for further occurrence, historical disasters can be used much more extensively as a currently available test laboratory for scenario discovery'[18]. To this we can add the idea of possibilism in which taking the largest extreme seriously, even without a robust estimate of probability, is important because of its potential to be extremely damaging[22].

The existence of very large magnitude events in the past is now well known. For example, mega-floods in the Siang river, NE Himalaya, had peak discharges of the order of 10^7 cumecs (cubic metres per second)[23]. Such events, which are several orders of magnitude larger than gauged floods, should be a reason for suspending building infrastructure in the same locations. Such events will occur again; we just do not know when or with what probability. Information other than the results of probabilistic analysis should be used in decision-making, opening up the discussion to wider views and doubts. Also, scenario planning based on 'stories' is a viable alternative and would complement the current standard methods.

Previous floods in Uttarakhand in 1893 and 1970 have been well documented[14]. But they appear to have had no impact on the decision-making. The 2013 event has also been well documented and it shared many characteristics with the previous events. This documentation is based on photographs, oral accounts, some flow records, evidence of damage to infrastructure, counts of the dead, and sediment deposits left behind by the floods. Such information will be immediately accessible to those trained in history, except the sedimentary evidence which provides a record of large events and those much longer than is available to the historians, but is accessible to the earth scientists.

A 1000-year record of very large floods in the Alaknanda river was obtained from flood deposits near Srinagar[13]. This record showed that, on an average, a very large flood occurred in this river every 40 years. However, the floods were clustered in time, so that the average is not robust and the series is non-stationary. This record was made available to the engineers involved in dam construction in Uttarakhand, after they claimed (to one of us, RW) that the 2013 event was unique. They appear to have known nothing of the historically documented floods, even though one might assume that anyone building a dam in a river would use whatever information he/she could find. Or did they deliberately forget a real phenomenon, which is an area of scholarly research called agnotology? Such records offer a wealth of information in many parts of the Himalaya[14]. However, it is not evident that they are being used for planning purposes. They have been ignored or even deliberately forgotten.

Tree rings can also provide information about large floods. It has been demonstrated that an improvement can be achieved in both the number of floods in the record and in regional flood quartiles in Himachal Pradesh, when tree ring damage data and gauged flow records are combined[4]. The results show that, based only on the gauged record, flood hazard is systematically underestimated. More such analyses along with palaeo flood records are needed in the HKH, as well as engagement with hydrologists and engineers in their applications.

Observations

Any person trained in the earth sciences would recognize in the Himalaya all of the features that give rise to large landslides, floods and debris flows, including LLOFs and GLOFs. Very steep valley sides, fractured rocks, earthquakes and intense rainfall that cause landslides and LLOFs, retreating glaciers leaving behind lakes that can cause GLOFs, and the deposits of former landslides, floods and debris flows are all testimony to the risk. More directly, very large boulders in the riverbeds, that require either velocities in water of more than 5 m s^{-1} or flotation in debris flow, are sure signs of danger. For example, boulders at the mouth of the Birehi Ganga, a tributary of the Alaknanda, before the 2013 flood had a mean diameter of about 2 m which requires a minimum velocity of water of at least 5 m s^{-1}, according to the equations of Costa[24]. If moved by debris flow, they are just as dangerous, as shown in the Rishiganga. Also, boulders on the margin of the Alaknanda at Bhainswara, downstream of Srinagar, before the 2013 flood had a mean diameter of about 4 m. The minimum velocity to move them is >7 m s^{-1}, the 2013 flood removed them. It also moved a large number of boulders, many of which were deposited in river valleys, thereby raising the riverbed and increasing the flood risk to riparian communities and infrastructure. Figure 1 is a photograph of such boulders near Sonprayag, Uttarakhand.

Such observations are standard for earth scientists, but not for (most) engineers, because of differences in the nature of training. Of course, the economic imperative affecting engineers designing and overseeing the construction of dams and hydels in the Himalaya is different from the motivation of most earth scientists working in these high mountains, leading to different observations and evidence bases. But, is it not possible to join forces?

What is also obvious is that local people are aware of what has happened and can happen again, but their views are neither sought nor heard. The importance of traditional knowledge (also known as indigenous or local knowledge) is now being acknowledged (https://www.icimod.org/event/trans-himalayan-environmental-humanities-integrating-indigenous-mountain-knowledge-modern-sciences-and-global-endeavours-for-a-sustainable-himalayan-region/; accessed on 30 April 2021) and should be included in any development plans for the HKH. Although human memory is not perfect, often the outlines of events are recalled, if not the details. When employed in 'downward counter factual analysis', memories and worst cases can be explored[25].

Information from the first principles of earth sciences and hydrology, on-the-ground observations by earth scientists in the HKH, historical documentation and the experience of local people can all be used to identify the most dangerous places in the valleys of the HKH, building on the obvious that these valleys are dangerous for the infrastructure that is now commonplace in some areas, but is yet to be built elsewhere. The possibility of frequent, large, destructive floods and landslides has already been demonstrated in Uttarakhand and in other parts of the HKH[14]. This is surely a topic of great urgency which should combine the skills of earth scientists, hydrologists, historians and engineers to map and document these events throughout the HKH.

While such an approach will clearly be of great value, much more needs to be done to exploit the natural sedimentary and tree-ring archives of extreme hydroclimatic events. Monitoring is also required, a topic to which we turn now.

An intelligent, multi-parametric observing system

It is imperative that countries develop a dedicated observing system for the entire HKH, that takes a holistic view of the physical processes at work, as described above. It is not adequate to make resolutions about better risk assessment and management after each event, and then relapse to a complacent state. What is needed is an integrated observing system that would comprise a dedicated geosynchronous satellite with multi-wavelength (visible, infrared and microwave) and cartographic capabilities to trace changes in landforms, soil moisture, lake formation and their breach potential, the integration of precipitation density monitors in real time, AI-based instrumented monitoring of landslide-prone areas, scenario-based simulation models of floods in each major catchment and their impacts (so that the most appropriate scenario is available at the time of any event), monitoring of noise for environmental seismology inputs and modelling of the probable impact of earthquakes in various regions. Initial ideas have been proposed by Shukla and Sen[26], and Rao *et al.*[27].

An intelligent, learning, hierarchical AI system is needed to provide real-time warnings based on the integration of multiple data types. In India, institutions such as the Wadia Institute of Himalayan Geology, the Indian Institute of Remote Sensing, the Institute for Snow and Avalanche Studies, and the National Geophysical Research Institute have the requisite and complementary expertise to deliver on such an observing system. Collaboration with the Indian National Disaster Management Authority could lead to an early warning system for all types of hazards in the Himalaya. If done well, it would be of benefit

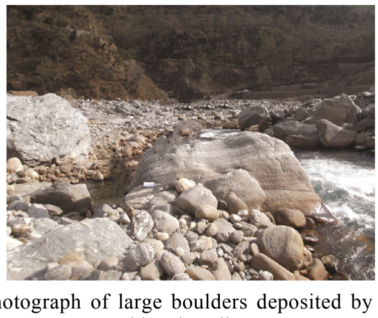

Figure 1. Photograph of large boulders deposited by the June 2013 event near Sonprayag, Uttarakhand, India.

to the people of the mountains as well as to science. For other HKH countries also such a system is also needed, and the entire system could be coordinated by the International Centre for Integrated Mountain Development (ICIMOD), Nepal.

Discussion and conclusions

The other topics that could be considered include possible disincentives for taking risk seriously in financing of infrastructure, the ethical issues in discounting future disasters and reducing human exposure and vulnerability to hazards.

If death and destruction are to be minimized in the HKH, urgent steps are required to develop a much better understanding of the risk from floods and other environmental hazards. We suggest that a moratorium be imposed on further development until then. An Indian Task Force of earth scientists, hydrologists, historians and engineers (civil and AI) should be established to chart a course for such understanding and to develop a comprehensive monitoring programme. ICIMOD may be approached to play a coordinating role among all the involved countries. Such a venture should examine both hazards and the ways to reduce human exposure and vulnerability. The idea of developing a Himalaya-centric institution having dedicated observatories both on land and in space should be mooted. The historical data on such hazards should thus be augmented with real-time long records issuing from these observatories, and analysed using machine learning tools and artificial intelligence. A scientifically informed mitigation policy suggested by an envisaged institution should be able to bring sustainability and reduce the risk of disaster.

Simultaneously we urge the responsible authorities and private sector companies to reflect upon their worldview. Is it one of 'domination of nature' and, if so, can it now be moderated by greater humility in the face of nature's ability to destroy much of that which humanity creates[8]? The arrival of the Anthropocene, while not familiar to many, we suspect, should result in far greater humility in those wishing to exploit the resources of the HKH. To continue on the current hubristic path is to invite continuing and increasing disaster.

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