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RESEARCH PAPER

Flood Mitigation, Climate Change Adaptation, and Technological Lock-in in Assam

Robert Wasson, * Arupjyoti Saikia, ** Priya Bansal, *** and Chong Joon Chuah ****

Abstract: Climate change adaptation requires communities and policymakers to be flexible in order to cope with high levels of uncertainty in climate projections, particularly of precipitation, flood magnitude and frequency, and changing human exposure and vulnerability to floods—which are even less predictable than the climate. Most of the world's major rivers are embanked to "protect" communities from floods. Embankments—which represent a significant investment largely of public funds—are a manifestation of the professionalism of engineers and hydrologists. They are also the result of professional and political entrapment and a technological frame that grows in strength (probably non-linearly) by positive feedback to produce technological lock-in. This results in inertia in large socio-technological systems, with little incentive to adopt more adaptive and flexible solutions, including non-structural measures—such as land-use zoning—even in the face of evidence that structural measures do not always reduce damage and, in some cases, actually make it worse. Where embankment breaches are common, damage is likely to increase as climate change induces larger floods, and lock-in and path dependence increase risk. Therefore, there is an urgent need for the mitigation of floods through non-structural measures that complement embankments. While

* College of Science and Engineering, James Cook University, Smithfield; 4878 Queensland, Australia; Fenner School of Environment and Society, Australian National University, Canberra 0200, Australia; wasson.robertj@gmail.com. ✉

** Department of Humanities and Social Sciences, IIT Guwahati, 781039, India; arupjyotisaikia@gmail.com.

*** Competition Commission of India, Ministry of Corporate Affairs, 9th Floor, Office Block – 1, Kidwai Nagar (East), New Delhi 110023, India; bansalpriya1994@gmail.com.

**** Tembusu College, National University of Singapore, 138598, Singapore; joon@nus.edu.sg.

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the phenomena we describe in this paper are common in many countries, as well as in many states in India, it will focus on data from the Brahmaputra River catchment in Assam.

Keywords: Flood Damage, Assam, Embankments, Technological Lock-in

1. INTRODUCTION

Even before Independence, India's main flood mitigation policy intervention has been the construction of embankments. While there are other flood mitigation strategies, including issuing warnings; providing refuges; creating rescue plans and emergency medical facilities; river dredging; and facilitating education, embankments are widespread and appear to dominate the thinking of decision-makers—if the speeches made by politicians after floods are any guide. The dominance of embankments appears to be an example of technological lock-in, whereby one solution gains ground and others are marginalized. Lock-ins produce inflexibility in decision-making, which, we argue, reduces the region's adaptive capacity given both current circumstances and future climatic conditions that may produce larger floods.

Climate change is likely to be accompanied by more intense rainfall and higher flood peaks in many of India's rivers (Kumar *et al.* 2013), but the uncertainties attached to climate projections make it unpredictable. This problem prompted Kumar *et al.* (2013) to comment that adaptation strategies should be both robust and flexible. In other words, keep your options open—which is the opposite of a lock-in, where options can be extremely limited. Before proceeding to a case study of embankment construction in Assam, we will make a foray into the key concepts of technological lock-in. While embankments are not particularly high-tech, we will show that the analysis of high-tech industries and activities can be applied to flood mitigation to generate useful findings. We suggest that the conceptual framework applied to high-tech industries and environmental management may have wider applications.

2. KEY CONCEPTS

2.1. Technological lock-in and system dynamics

Most studies of technological lock-in have been in the realm of manufacturing, particularly the production of high-tech goods. But some have also paid attention to examples in environmental management (Kline 2001), such as the lock-in of pesticide use for pest management and in hydrocarbon-intensive industries (Arthur 1996; Unruh 2002). While they differ from the case of embankments as a form of technological lock-in, studies of high-tech manufacturers nonetheless provide useful guidance and analogues for key concepts that help explain historical trends in flood mitigation policies. They also identify ways to unlock the locked.

There are two general explanations of lock-in. The first is the idea that lock-in reflects what Nelson and Winter (1977) describe as "technological regimes" (or epistemic communities), whereby rules, heuristics, or principles define the boundaries of thought and action, particularly those of technocrats such as engineers. This leads to specific directions of development that build on past experience, becoming very powerful means that exclude other solutions (Dosi 1982). Second is the idea of increasing returns (or benefits). This involves positive feedback, whereby the attractiveness of a particular technology increases the more it is adopted (David 1985; Arthur 1989). Positive feedback (also known as reinforcing feedback or "success to the successful") is a system dynamics (SD) concept according to which the direction of change is reinforced (Meadows 2008). That is, if variable A increases (or decreases) then variable B will increase (or decrease), all else being equal. But variable B can also affect variable A, thereby forming a positive feedback loop. In different words, a feedback process (or loop) involves at least two coupled variables, where an initial change (or perturbation) of one (A) causes a change in the other (B), which causes further change in the first (A). For more insights into these processes in relation to floods, see Barendrecht, Viglione, and Blöschl (2017), Srinivasan *et al.* (2017), and Newell and Wasson (2002).

2.2 Socio-technological realms, techno-politics, technological frames, and political and professional entrapment

The variables in SD are usually represented as stocks, that is, accumulations of materials, information, or ideas in a system over time (Meadows 2008). The feedback between stocks is conceptualized as flows that change their size. In relation to the problem of technological lock-in concerning flood mitigation, it is useful to refer to the idea of technological regimes, whereby a set of ideas (and methods) among engineers, bureaucrats, and politicians shape the development of policy and its implementation in a socio-technological realm (Colven 2017) where society is moulded by technology and vice versa—creating another set of feedbacks. But in the words of Bijker (2007), dikes (also known as embankments, levees, or bunds) and dams are thick with politics (with a lower case "p", so not only the politics of politicians). That is, they are not just a technical matter that need design and implementation. This idea can also be constructed as a form of techno-politics, where technology, politics, and society are co-produced, and a techno-political network formed, bringing together political-economic interests, globalized expertise (consultants in particular), and flows of capital (Sneddon 2015), all by the medium of positive feedback. Kaika (2006) goes further to argue that large water infrastructure projects are central to state-building, developmentalist agendas and the pursuit of modernity, and symbolize the control of nature.

While positive feedback is in place, the system will head in a particular direction. But the construction of embankments will eventually lead to the development of a negative feedback loop as, for example, the cost of maintenance increases. A negative feedback loop is one in which as variable A increases (or decreases), variable B decreases (or increases) and then feeds back to variable A. This is a stabilizing loop.

Though some believe there is a trend toward softer approaches to flood mitigation to complement (or even replace) hard engineering solutions—which have dominated in the so-called "hydraulic age", most notably in the Netherlands (Rijke *et al.* 2012)—the creation of technological regimes, socio-technological realms, and techno-politics, all with strong positive feedback, have created, in many countries, obdurate practices and value systems. As Bijker (2007) sees it, people deeply engaged in these technological frames have difficulty imagining other ways of dealing with risk. A good example of this is the US Army Corps of Engineers, whose only solution to flooding for many decades was the construction of levees. The "hydraulic age" is not over, as we can see in Indonesia, India, China, Australia, and elsewhere. In fact, it never went away, as evidenced by the recent upsurge in the construction of large dams (Merme *et al.* 2014).

For Brown, Ashley, and Farrelly (2011), these technological frames represent political and professional entrapment where there is political risk in moving in a different direction or not taking action after a flood—for example, by promising more (visible) protective infrastructure, fearfulness on the part of professionals in government agencies to speak their minds and therefore challenge the agency's position. There is also a fear among professional government agencies of losing their power if a broader set of mitigation strategies is contemplated, especially if there is to be a hybrid governance system that involves wide participation. Obdurate institutional arrangements, technological frames, and political and professional entrapment maintain and enhance the status quo, whatever it may be. To this rich mix, we can add the financialization of infrastructure (Loftus and March 2015). Investment in infrastructure is considered a way of mopping up over-accumulated capital in the over-developed world. Analogous to the case of the London desalination plant (whose main objective, according to Loftus and March (2015), was ensuring inflation-protected returns for institutional investors rather than the provision of clean water), embankment construction in many less developed countries appears to be about securing profits for construction companies, kickbacks to elites, and political power. Many countries do not emulate the objectives of the Dutch, who build dikes to keep the water out at all costs. By contrast, in the United States, the government accepts flooding, even in the presence of dikes, and places more reliance on insurance and warnings based on predictions (Bijker 2007). Both countries, of course, have a very different set of experiences of floods, and in the Netherlands, flood protection is an existential issue. In India, the objectives are the protection of lives, property, and revenues to the state by the total exclusion of floods from areas beyond embanked rivers.

2.3. Historical triggers

The Brahmaputra River in Northeast India rises in Tibet and flows through the Tsangpo Gorge to become the Siang River. Then, after being joined by many tributaries, it becomes the Brahmaputra, and leaves India at the Bangladesh border (Figure 1). In Assam, the floodplains of the Brahmaputra and its tributaries are extremely flood-prone, having experienced a total economic damage of ₹20,772.76 crore (10^7) to crops, housing, and public utilities between 1953 and 2011 and an average annual economic damage of ₹352.08 crore (in 2017 prices), according to data made available by the Central Water Commission (CWC). The range of annual total flood damage in Assam is enormous, from an estimated minimum of zero (which is of uncertain veracity) to ₹3,394.84 crore. The people of Assam would be better off with more effective flood mitigation. But first the government would need to reduce its reliance on embankments and help overcome technological lock-in.

As we have already explained, technological lock-in is a result of positive feedback that produces path dependence—continued adherence to a product or idea because of the historical trajectories of ideas and decisions, even in the presence of better products and ideas (Liebowitz and Margolis 1995). These trajectories may start from small beginnings or triggering events. This suggests that history matters in lock-in, an idea brought to the fore by Arthur (1989) in the case of competing technologies.

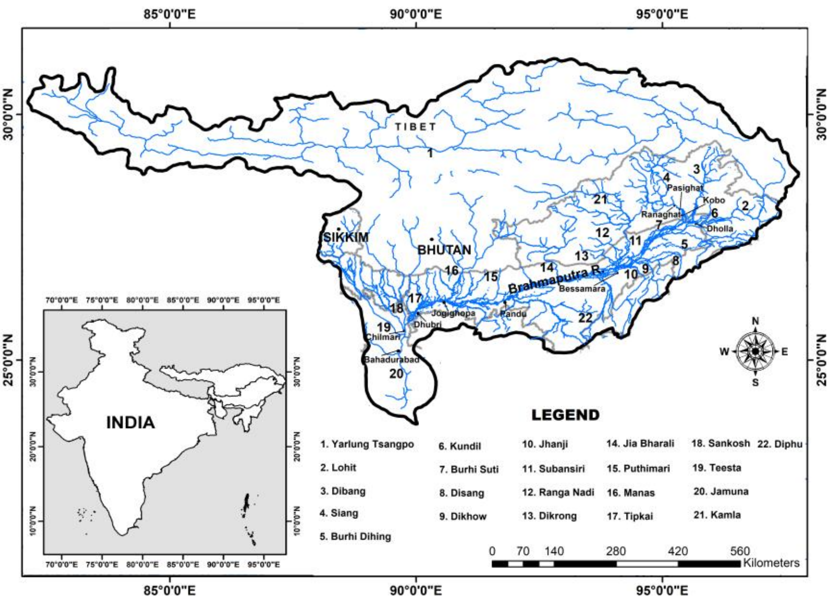
For positive feedback systems, it is worth quoting Arthur (1989):

> Insignificant circumstances become magnified by positive feedbacks to "tip" the system into the actual outcome "selected". The small events of history

> become important. Where we observe the predominance of one technology or one economic outcome over its competitors, we should be cautious of any exercise that seeks the means by which the winner's innate "superiority" came to be translated into adoption. (127)

In other words, that a particular technology, such as embankments, has won the race does not make it superior to its alternatives. The superiority of any technology needs to be demonstrated independent of the path by which it came to dominate the field.

Figure 1: A map of the Brahmaputra River and its catchment from Tibet to Bangladesh



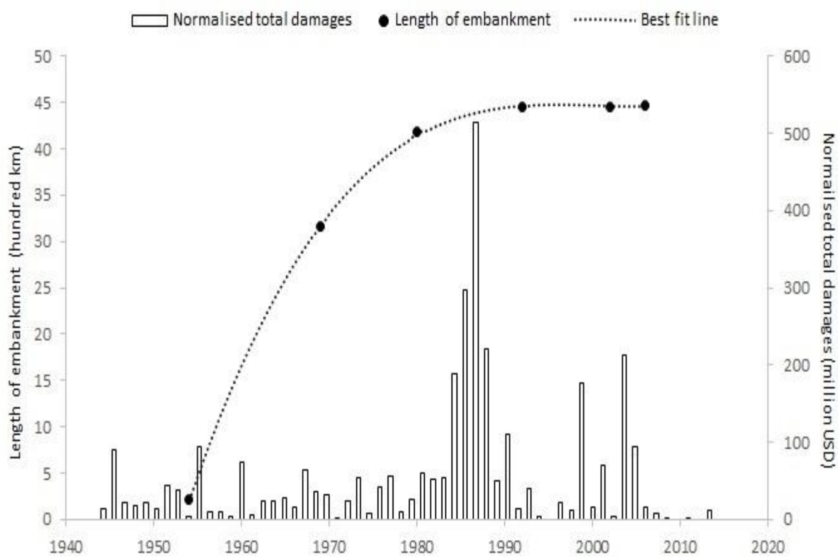
Source: Shukla Acharjee, Dibrugarh University

The disproportionate response to a "small event" (in this case, a flood)—the building of many hundreds of kilometres of embankments—shows that the positive feedback is non-linear. The quantitative nature of this relationship is unlikely to be exponential or super-exponential, because each of these functions implies increasing resourcing at an accelerating rate. The most commonly used function to describe the diffusion of innovation, including infrastructure, is the logistic curve:

$$f(X) = L/1 + e^{-K(X - X_0)}$$

where e is the natural logarithmic base, X_0 is the X -value of the sigmoid's midpoint, L is the curve's maximum value, and K is the steepness of the curve. The curve is S-shaped, rising to the midpoint; then it increases at a decreasing rate. This function has been used to model the spread of innovation, with an initial exponential spurt of activity and then a slowdown, as competitors become more effective (Grübler 1990).

Figure 2: Length of embankments and normalized total economic flood-related economic damages in Assam from 1953 to 2012



Source: Partha Jyoti Das, pers. comm. 2018 for embankment data and Central Water Commission for the damage data.

Data from Assam (Partha Jyoti Das, pers. comm., 2018) suggest a variant of the standard logistic curve, with a rapid increase in cumulative embankment length, which increases at a decreasing rate until the rate of change drops to zero from the early 1990s (Figure 2). The initial increase is a result of the early effects of positive feedback with high levels of enthusiasm, expectations, and resourcing. The slowdown may be a result of decreasing opportunities for construction, rising costs of maintenance, and a slowing of revenue injections as other priorities take over. We would require a detailed history of embankment construction and associated costs to test these explanations of the curve in Figure 2. However, the Comptroller and Auditor General of India (2017) provides some insights into the possible reasons for the slowdown: delays and shortfalls in the sanctioning of funds;

the diversion of funds sanctioned for flood control to unapproved work; major delays in work; poor design and implementation, leading to embankment failure; and weak technical skills in the states responsible for flood protection. All of these factors can slow the development of flood mitigation infrastructure.

Figure 2 is an example of an external-influence logistic function, the basic model for which is

$$\frac{dN(t)}{dT} = a[Nt - N(t)]$$

where $N(t)$ is the cumulative number of adopters at time t, N_t is the total number of potential adopters at time t, $\frac{dN(t)}{dT}$ is the rate of diffusion at time t, and the constant a is a change agent that is equal to the coefficient of diffusion (Kumar 2015). For application to the problem of embankment construction, adopters and potential adopters are assumed to be equivalent to the length of embankments. The key difference between this equation and others presented by Kumar (2015) for cases where there are external influences, and mixtures of external and internal influences, is the inclusion of the constant a, a change agent. When influence comes from outside the wider society, decision-making is directed from the top, and communication is strongly hierarchical (Kijek and Kijek 2010; Kumar 2015). In Assam, the change agent is the politico-bureaucratic system.

The best least squares fit for the trajectory of cumulative embankment length in Assam (Figure 2) is a four-parameter logistic curve:

$$Y = -11.43 + \frac{(44.76 + 11.43)}{1 + 10^{(\log 1961 - X)0.06751}}$$

where Y is cumulative length (100s of km), X is calendar date, the halfway point is 1961, and the r^2 is 0.99, but with only six data points.

2.4. Unlocking the locked

The obvious way to unlock the locked is to initiate negative feedback. According to Arthur (1989), small historical events, such as small-scale trials of non-structural mitigation, will have no effect on this type of system, and history will be the carrier or deliverer of the inevitable. But a major flood that devastates an area where alternatives to embankments have been trialled could tip the system back into its former state of positive feedback, leading to the construction of more embankments.

There is, however, a larger problem. As we have seen, technological frames, professional and political entrapment, and lock-in are highly resistant to change. An easy exit from a locked-in trajectory is unlikely because of significant sunk construction costs, the development and application of particular kinds of expertise, the political capital expenditure a change would entail, and reputational risk if a decades-long policy is suddenly reversed. For example, revenues to construction companies in the case of large infrastructure projects and kickbacks to elites will also be at risk if a major policy change is instituted. Nevertheless, according to Islas (1997), hybridization can allow marginalized solutions to emerge beside the dominant one, but only in niches not occupied by the dominant solution.

2.5. Summary of key concepts

A technological lock-in results from technological frames—stocks of ideas developed by professionals and decision-makers—that limit the range of solutions considered during policy formulation. Locked-in solutions are not necessarily superior just because they have been overwhelmingly adopted. We must determine superiority independently. There are many elements to technological frames, including socio-technological realms, political-technological networks, and professional and political entrapment. A system's trajectory will be unidirectional if positive feedback is in play once a historical event triggers a trajectory—and therefore path dependence—that favours one technology or solution. As adoption increases, positive feedback in response to the ideas in the technological frame increases its power and acceptance, and more resources may become available, driving a non-linear response. In this process, other solutions are swept aside in the battle of ideas and the struggle for resources. There could be a slowing in the rate of adoption of embankments as space for easy construction reduces. Enthusiasm may also wane, especially in light of the damage created by breaches; and maintenance costs may increase along with other calls on the public purse. The result is a positive feedback function in Assam, which is a variant of a logistic curve that denotes external influences on the construction of embankments.

It may be possible to unlock the locked by creating a negative feedback system, a prospect that is extremely difficult to achieve if the lock-in is obdurate. A path more likely to succeed would involve the development of a hybridized set of solutions, where we can find alternatives to the dominant solution in niches that it does not necessarily deal with well—or we could find solutions that complement the dominant one.

3. THE HISTORICAL DEVELOPMENT OF A TECHNOLOGICAL FRAME IN ASSAM

Colven (2017) notes that to understand the allure of big infrastructure, "we need to trace the emergence and evolution of the geographically and historically contingent techno-political networks through which such projects emerge" (261). This section attempts for Assam what Colven suggests, and is based mainly on Saikia (2019, Chapters 2, 7, and 11).

As early as the sixteenth and seventeenth centuries, embankments (also known as *alis* in Assam) were constructed to protect small areas from floods, and for many years, farmers used low-level bunds to reduce the impact of floods but also to allow water and sediment to reach fields. This resulted in localized and moderate benefits. By the first few years of the twentieth century, there were only 180 km of high embankments in Assam. A committee established by J. B. Fuller, the Chief Commissioner of Assam under the British Raj, investigated the possibility that embankments could allow larger areas to be cultivated and damage to crops reduced. It examined additional questions that are still pertinent today, many of which have not been answered satisfactorily, such as: what would be the consequences of depriving land of silt and its natural fertilizing role? Peasants interviewed by the committee raised this issue; they also raised issues of waterlogging behind embankments, pointing out their failure. In addition, they asked if riverbeds would rise relative to floodplains because of sediment accumulation between embankments and due to sediment starvation on the floodplains behind embankments. The committee also wanted to know if larger areas of cultivation would increase revenue, a key concern for the British Raj.

The Fuller committee received varying opinions about the wisdom of embankment construction, ranging from views that embankments were not necessary for the protection of agriculture—as there was plenty of cultivable land—to beliefs that riverbeds may either rise by sediment accumulation (relative to floodplains) or decline because of erosion by high-velocity flood flows trapped between embankments, and concerns that the revenue increase from protected land would be much smaller than the cost of constructing and maintaining embankments. However, the committee found evidence in favour of embankments, and in 1903, received approval for the construction of new embankments on two tributaries of the Brahmaputra, followed by increased land revenue assessment.

But the debate about the wisdom of embankments continued, largely revolving around concerns regarding the lack of natural fertilization and the problem of waterlogging, as embankments prevented the drainage of floodwater and presumably ponded rainwater (Hart 1906). In the past, during particularly wet seasons, peasants would relocate to drier land, but this became difficult when property laws became less flexible and the population and the area of settled agriculture increased during the British period, thereby making the relinquishment of land almost impossible. For some people, waterlogging became an intractable problem. The agricultural chemist and soil scientist, A. A. Meggitt, supported the peasants' view that natural fertilizing was essential, and suggested the installation of flood sluice gates to enable this process (Chief Secretary 1909). Lechmere-Oertel (1918), an engineer with the Public Works Department, argued against embankments on the same grounds as Meggitt. Additionally, Spring (1903), the Chief Engineer of India's Public Works Department, wrote in praise of the traditional method of living with floods, whereby people moved their meagre possessions to higher ground in family boats.

To this contentious milieu was added the construction of railway lines on embankments from 1903 onward, most of which were built on floodplains by 1930 (Public Works Department 1929–30). These embankments disturbed lowland drainage paths and therefore blocked the drainage of floodwaters, rendering some low-lying areas unfit for cultivation and causing havoc when they breached (The Times of India 1934). An investigative committee formed after the 1929 flood found conflicting views among peasants, depending on whether they lived "inside" or "outside" a railway embankment (Lines 1930). Those "outside" the embankments were content, while those "inside" were not.

By the mid-1930s, flooding in Assam was gaining more attention from both the government and the international press (e.g., Western Argus 1934) with widespread destruction of crops, houses, and livestock (Wall Street Journal 1934). For the colonial government, the impact on revenue of the destruction of jute crop was particularly important, as the Brahmaputra Valley had become the principal jute-growing area in South Asia by the 1930s. This widespread cultivation of jute followed debates about the wisdom of using land that the local people did not cultivate because of flooding, except for temporary mustard and vegetable crops during the winter and some summer rice, although jute was believed capable of withstanding floods (Saikia 2015). But the influx of peasants, mainly from East Bengal (now Bangladesh), mostly to grow jute, was well underway, making the debate almost pointless. Between the censuses of 1911 and 1951, 1–1.5 million migrants had moved into Assam, constituting between one-tenth and one-sixth of the total population. The cropped area approximately doubled, areas of settlement increased, and the cultivation of jute, sugarcane, mustard, and winter and autumn rice increased in the areas occupied by these hard-working migrants (Doullah 2003; Goswami 1994; Chakraborty 2012). This transformation of agriculture in Assam was not only aided by the construction of embankments—embankments were themselves necessary for the maintenance of increased revenue flow to the government's coffers.

After the flood of 1934, Shaw (1935), an engineer with the Public Works Department, prepared a report in which he noted that the area was prone to some of the heaviest rainfall in the world and, when combined with large-scale reclamation of land for jute cultivation, much of the lower valley was at risk of economically damaging floods. Shaw also argued against embankments, writing that they "constitute a gross interference with the natural regime of the river" (8). He listed solutions such as relief payments to peasants, remission of land revenue, and new land grants, some of which were enacted (Saikia 2014). In addition, he found that the new migrants who arrived to grow jute did not grow food, so they became vulnerable to flood-induced food shortages.

The 1946 flood in Assam spawned yet another report, this time by S. C. Majumdar, an engineer with considerable experience of floods in Bengal. Majumdar (1948, 1956) concluded inter alia that embankments defy nature and should only be used on rivers that are relatively stable, and that embankments can cause disasters by raising the intensity with which floods reach floodplains, because of sedimentation within channels between embankments, thereby causing more damage than would occur without embankments and also resulting in the need for higher and stronger embankments until they provide no protection. He added that embankments should not be viewed as permanent solutions, and the old embankments of the sixteenth and seventeenth centuries CE created vast swamps at a lower level than the surrounding land, which continued to receive sediment. Majumdar made the obvious remark that floods are shallower and less dangerous if allowed to spread across floodplains rather than being pent up behind embankments that can easily breach.

The bureaucrats of Assam continued to oppose embankments, so that by 1947, there were only 11 km of new embankments (RBA 1980). The Government of India declared embankments unsuccessful as flood protection devices (Ministry of Information and Broadcasting 1949); after the 1950 earthquake and floods, the technocrat G. C. Garg and Kumud Bhushan Ray (special officer for rivers in Assam's Public Works Department) advised against embankments. Ray (1954) concluded that embankments were costly and non-remunerative, and did not provide protection against large floods.

Prior to 1954, there was no unified technological frame in favour of embankments in Assam. Many bureaucrats and engineers were not convinced of the efficacy of embankments. They cited the unintended consequences of waterlogging, sand deposition on agricultural land during breaching, and reduced natural fertilization of fields through sedimentation. By this time, there had been many flood events (the "small events" referenced in Arthur [1989]) that could have triggered the consolidation of a technological frame in support of embankments, particularly in 1929, the mid-1930s (especially 1934), 1946, and 1950, each of which was followed by a government investigation. But none of these events triggered this consolidation.

The 1950 earthquake, with a magnitude of 8.6, devastated Assam, and was followed in 1952, 1953, 1954, and 1955 by severe floods that damaged crops worth ₹13.5 crore in 1953–1955 (₹520 crore and US$2.1 million in 2017 prices; there are no data for 1952) and destroyed 65% of the paddy and 53% of the jute. It was claimed that inundation covered 31,000 sq km (an implausible 40% of the state), and affected about 1.2 million people (Assam Government 1956). These floods eroded riverbanks and swept away agricultural land, villages, and lives, depositing sand on land that had once been cultivable. Some towns vanished while others faced massive erosion. The town of Dibrugarh had begun serious attempts at riverbank protection in 1935 after the 1934 flood, with anchored trees, brushwood screens, tree branch revetments, and anchored floating bamboo cages. Some 450 m of a planned 6 km stone revetment was finished before the monsoon of 1954 struck, and floodwaters outflanked the entire structure. The situation was so serious that the then Prime Minister, Pundit Jawaharlal Nehru, took charge and paid a visit, entrusting to the Central Water and Power Commission (CPWC) with the responsibility of protecting the town from further floods (Ray 1956; Singh *et al.* 2004).

The flood of 1954 not only swept away lives—it also swept away apprehensions about embankments, at least in government offices. A simplified version of the Assam Embankment and Drainage Act 1941, enacted in 1954, enabled embankment construction. About 855 km of embankments were completed swiftly (Verghese 1954). An Indian delegation to China reinforced the value of embankments (Sain 1954) and Reddy (1954) provided a glowing report on China's use of embankments to control floods. Engineers of the CPWC began arriving in Assam, training in surveying and construction methods was arranged, and labour for embankment construction recruited (Verghese 1854).

The flood of 1954 was the "small event" in Arthur's (1989) conceptualization of how positive feedback is triggered by a seemingly insignificant event and leads to an outcome that is disproportionally large. As a result, one option gets locked-in, and path dependence begins. These small events of history are important, and although the residents of Assam who lost their property and loved ones may not see the floods of the 1950s as "small events", they appear to meet the requirements of Arthur's model. But why did the earlier floods not create the same path dependence? The answer may lie in the personal intervention of India's first prime minister and the institutionalization of a response in the CPWC. Whatever the answer, it is clear that the 1954 flood turned the tide of government opinion—and thus path dependence began.

The most visible protection works were in the town of Dibrugarh, which had suffered serious flood damage. Embankments built in 1954–1956 were raised and strengthened in 1963–1966, 1977, and 1980, and again after flood damage in 1988, and to this day continue to be refurbished, partly as a result of the heightened level of floods resulting from the increasing channel bed level (UN-Habitat 2002; ADB 2009).

Other ideas were proffered to mitigate floods, such as cleaning drainage channels, digging a deeper channel for the Brahmaputra (which has now been trialled), beginning reforestation of the catchment to slow storm runoff, raising villages, and constructing storage reservoirs (Kingdon-Ward 1950; The Times of India 1954; Ray 1956). But the push for embankments was well underway, along with the restoration of some abandoned channels to promote drainage, the digging of new drains, and the promotion of sedimentation in some areas to raise land levels (RBA 1980). Although some still doubted the efficacy of embankments in the face of mighty natural forces, by 1978, a total of 4,000 km of embankments had been constructed in Assam, along with at least 700 km of drainage channels. Breaches had occurred in some new embankments within a year of construction, and some caused conflicts with villagers, but construction continued, as those in favour of the policy continued to accrue political and economic benefits. By the end of the twentieth century, about 1,000 km of embankments had been constructed along the Brahmaputra, measuring about two-thirds the total length of the river. Since then, embankments have been further extended along tributaries. Rivers in about 50% of Assam's total flood-prone area were embanked about a decade ago (Asian Development Bank 2010).

Our field observations and informal discussions with villagers and government officials in Upper Assam show that many people have now become dependent on embankments for refuge during the worst floods. Some have replaced their traditional stilt houses with concrete constructions on the ground. Similarly, they have also built schools and meeting halls near embankments; and they are now using previously uncultivated land just behind embankments. Hazarika *et al.* (2016) found from surveys in Dhemaji District that the construction of embankments has attracted several people to live and cultivate the land near the rivers, and that the occurrence of floods, in the minds of local people, is synonymous with breaching of embankments. According to their study, even though embankments are refuges, breaches do more damage than floods in places where there are no embankments.

Many factors have produced the current, embankment-dominated flood policy in Assam. The most important ones appear to be a need to protect valuable assets such as towns and cultivated areas; increase the area of cultivation; and protect and increase government revenue from cash crops, the most important of which was jute. This process has a history of more than a century, with the establishment of jute and the importation of migrants from East Bengal to grow the jute, both initiated by the colonial government. The path dependence of increasing embankments resulted from positive feedback between the maintenance and protection of cash crops and revenues, and from technological entrapment and a growing technological frame.

The historical trigger for this path dependence was the flood of 1954, even though there had been earlier floods of similar magnitude with similar destructive outcomes. Political involvement and institutionalized responses appear to have tipped the balance in favour of embankments, and the technological frame established was able to sideline differing views about the efficacy of embankments.

4. THE FITNESS OF EMBANKMENTS

Fitness is a concept that analysts of high-technology products use to decide whether path dependence produces the most fit goods—or something that is sub-optimal. While Arthur (1989) argued that sub-optimal outcomes are common, later researchers criticized this conclusion (e.g., Islas 1997).

While a full exposition of ongoing research by the authors into this important topic is not possible here, we have analysed data from the CWC for trends in death and economic damage, normalized by total population and GDP/capita, respectively. Using the non-parametric Mann-Kendall Tau (b) test for all-India data, we have found an increasing trend in adjusted damage from 1953 to 2011 ($p<0.01$), but no trend in adjusted deaths. However, from 1982 to 2011, when embankments were much more extensive than earlier, normalized deaths decreased ($p<0.01$), but there is no trend in normalized damage. The area affected by floods also declined between 1982 and 2011 ($p<0.01$), confounding any simple explanation of these results, although the smaller area of flood-affected land may explain the reduced deaths. This complication notwithstanding, Figure 2 shows that normalized total economic damage was at its highest between 1986 and 1989, when the length of embankments was almost at its greatest extent. It is not at all clear whether embankments make a large difference to deaths and damage because breaches occur during large floods, or because embankments are outflanked when incomplete—a result consistent with the modelling results of Barendrecht *et al.* (2017).

5. RIVER LINKING: ANOTHER POWERFUL TECHNOLOGICAL FRAME

The long-standing technological frame created by engineers, hydrologists, bureaucrats, and politicians lives on in India, exemplified by the River Linking Plan (Alley 2004; Rao 2003). This ambitious plan to link India's major rivers aims to provide irrigation water to drought-prone areas, generate additional hydroelectric power, and reduce the extent of flooding. The scheme calls for the construction of a great many dams and canals. It is not at all clear how the plan will alleviate floods, except possibly by building large dams to absorb flood flows—an uncertain option if the dams are mainly intended for the supply of irrigation water and the generation of hydroelectricity. Simultaneously meeting these three objectives is not easy. Rao (2003) notes that the likely transfer from the Ganga to the Cauvery River, for example, will amount to only 2.5% of the maximum flood flow in the Ganga, a figure too small to have any effect on floods in the Ganga. But there do not appear to have been any publicly available analyses of the ways in which the plan may alleviate flooding. Alley (2004) argues that scientific data and detailed plans for the scheme are deliberately withheld from public scrutiny, leaving non-government experts and members of NGOs no option but to polarize the debate and reject the scheme, given that its risks cannot be analysed independently and appear large in the absence of other information.

The solution to big water problems in India continues to be big infrastructure projects, where a strong technological frame sidelines all objections and alternatives. The creation of a broad-based and knowledgeable epistemic community is not possible, so aspects of the scheme that should be assessed outside its formative technological frame are not assessed, and serious problems may emerge. For example, about 34% of the gross erosion of Indian soils is deposited in reservoirs, with a resulting annual average water storage loss of 1.04% and an upper value of 0.8% per annum in large reservoirs (51>1000 mm^3 capacity) (Sharda and Ojasvi 2016). Is this loss of storage capacity, and the attendant loss of flood absorption, being considered in government planning for river linking? Further, the state has prepared Emergency Action Plans for only 7% of the existing large dams in India and Operating Manuals for only 5% (Comptroller and Auditor General of India 2017). If the river linking scheme is to generate many more large dams, how will it ensure their safety, given the slow development of preparedness to date?

6. CONCLUDING REMARKS

From the analysis presented here, it appears that there has been lock-in of embankments in Assam as the main flood mitigation strategy. This is a region characterized by an extraordinarily volatile and fluid landscape, and it appears that lock-in may also have occurred in other Indian states as well (see D'Souza 2006). An analysis of death and damage data shows that though embankments have had some effect, they have certainly not solved the problem. In some cases, they have exacerbated deaths and damage when they have breached or have been outflanked. So lock-in has produced a sub-optimal result, but one that has nonetheless had some benefits, such as acting as a refuge and protecting some land and villages.

A major shift in Indian flood mitigation policy away from embankments appears to be unlikely, since it is driven by a top–down approach. We have seen this in the external influence logistic descriptor of the history of embankment construction in Assam and the prevailing strong and obdurate technological frame, exemplified by the river linking project. It is more likely that policies that complement embankments will succeed only if they fill a niche not already occupied by embankments. Such policies are floodplain planning and the enforcement of zoning; better warnings; implementation of the building code; insurance; relief schemes tailored to levels of risk, so that those who choose to live or rebuild in high-risk areas get little or no flood relief apart from humanitarian aid during and immediately after a flood; and relocation of highly exposed and vulnerable populations. These solutions may be applicable where embankments have not been built, and in the long run, they could demonstrate an approach that will replace embankments.

We require a more flexible and holistic set of flood mitigation policies in the face of climate change, given that rainfall intensities and flood peaks are likely to get larger. Embankments alone are insufficient, and at times, even dangerous.

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