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Will Climate Change Disrupt Tropical Development? Lessons from Economic History

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Abstract

The economic emergence of societies in arid and semi-arid tropical regions depended on their ability to extract and recycle water and manipulate the environment for this purpose. India is a prominent example of this process. This pathway to economic growth has significant political and environmental costs. In light of climate change, a key question for the future is: Is tropical development sustainable in this way? The paper answers by drawing on the economic history of the tropical arid regions and a recent literature on climate impact on water resources.

High economic growth in parts of the semi-arid tropics has contributed to an ongoing convergence between countries since the 2000s. South Asia is a prominent example of growth resurgence. Although most assessments of South Asia's emergence focus on non-agricultural investment, land productivity growth has been substantial, continued, and supported the non-agricultural economy. Sub-Saharan Africa has experienced a somewhat different pattern of economic change in recent decades. Investment in agriculture and outside it has grown, but economic growth remained (as in the past) subject to swings (Broadberry and Gardner 2022). Agriculture has contributed to economic growth, mainly via land extension and conversion of pasture and forest lands, and to a smaller extent than in South Asia, via land yield (Ndii 2022). Assessments of the sustainability

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of Sub-Saharan Africa's recent growth experience, however, consistently and forcefully emphasize the need to act on land and labour productivity in agriculture, though the recipe varies (Gopal and Nash 2017; Ndii 2022).

These initial remarks are meant to underline that the tropical world's economic prospects depend crucially on using local natural resources, mainly water. Indeed, all studies of agricultural prospects stress water extraction and control of water resources as a crucial precondition for land productivity growth. This stress is a common factor between South Asia and Sub-Saharan Africa. It is also a clue to the persistent divergence between these two parts of the tropics: South Asia, thanks to a stronger monsoon and snowmelt rivers, has more recyclable water resources on average. Water contributes in more ways than irrigation. Hydropower generation increased substantially since the 1960s in both regions. Presently, it provides a significant share (35-40 per cent) of electric power in Sub-Saharan Africa and about 15 per cent in South Asia (8 in India).[1] Dams to trap river water also generated power and were a device to control monsoon flooding.

A warming of the climate will almost certainly impact water sources and use. Will climate change make the productive use of water harder? Will it disrupt the long-term pattern of economic change in South Asia by changing the condition of water resources and the cost of recycling water, and will it pose a harder obstacle to transforming African agriculture? Is tropical development sustainable under climate change? This paper is a preliminary attempt to answer these questions.

The future of tropical development is dire if we follow what we read in the media. '[C]limate crisis,' says *The Guardian* (2021), 'is pushing the planet's tropical regions towards the limits of human liveability.' The World Economic Forum predicted in 2021 that 'more record-breaking temperatures will occur in the tropics.' *New York Times* said in 2022 that 'Climate change is making the South

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[1] https://data.worldbank.org/

Asian monsoon increasingly violent and erratic.' 'Climate change will expand the range of tropical cyclones,' says BBC.

Besides the issue that scientific studies about climate future do not speak in one voice, these predictions do not answer whether climate change will impact natural resource conditions and their distribution over time and space. The link between cyclones and the availability or use of resources (and, therefore, long-term growth) is not apparent. Meteorological future and hydrological future are different things. There is a connection between the two, but one mediated by many variables. This paper is interested in the hydrological predictions. Further, droughts and floods are not happening for the first time in the arid tropics. These events have a long history, and human adaptations to them also have a long history. What did societies do in the past to deal with a climatic type that regularly produced droughts and floods? Would those same steps sustain and save them under a changed climate?

The paper explores how climate change might impact tropical development (via water pathways). The paper has four parts: a definition of the climate type semi-arid or tropical monsoon (the next section); a theory of economic history, showing how this climatic type impacted economic activity in the past and how societies adapted or responded to the climatic condition (the third section); a review of the recent literature on climate change to draw robust results on the potential impact of climate change on the natural resources that matter most to tropical development (the fourth section); and a return to the question: Would past patterns of adaptation sustain under a changed climate (concluding discussion)?[2]

The Tropical Monsoon Climatic Type

Descriptions of the tropical climate emphasize an attribute called seasonality, the sequence of very dry and very wet seasons during a year. Tropical

[2] Section II draws on my recent works on the subject, including Roy (2021, 2022a, 2022b, and 2025).

seasonality with 'high temperatures and evaporation rates in addition to highly variable and unreliable rainfall' is a distinct climate type from its theoretical opposite, temperate climate (Agnew 1982: 423). '[T]he degree of seasonality in precipitation [is the] most pronounced in the tropical and subtropical ecoregions and generally low in the predominant ecoregions of the northern hemisphere' (Lisovski, Ramenofsky and Wingfield 2017). By contrast, the temperate zones are temperate because of lower average heat (low evapotranspiration rates) and an even distribution of rains during the year. Evapotranspiration is the process by which water is transferred from the Earth's surface to the atmosphere. The rate depends on solar radiation, air temperature, vapour pressure deficit, wind speed, and the characteristics of plants and vegetation.[3]

In development studies, 'semi-arid tropics' refers to areas with enough rainfall to enable rainfed farming but where the rain is uncertain from season to season (Jodha and Vyas 1969; Walker and Ryan 1990). I use a broader definition that is less rooted in the monsoonal cycle. Semi-arid tropics are areas where a high maximum summer temperature (exceeding 50°C or 122°F in many regions) prevails over weeks, even months at a time. Excessive heat evaporates surface water rapidly (evapotranspiration rates exceed the rate of moisture inflow), and occasional rains on baked soil cause high runoffs. Surface water is the cheapest water to access. It is an extremely scarce resource, with a high degree of contamination, in tropical monsoon areas for some months of the year.

The summer is broken by significant moisture inflow in some weeks or months. Parts of the regions experience seasonal floods and rains owing to the intertropical convergence zone, or ITCZ, known in many places as the monsoon.[4] Monsoonal moisture distribution is highly concentrated. A long arid and a short

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[3] The vapour pressure deficit is the difference between the amount of moisture in the air and the moisture the air could potentially hold, a relatively high value indicates that the air is too dry, and therefore faster transpiration and drying of plants.

[4] The mechanism is this: hot air rises and expands near the Thermal Equator (5^{o} North or South), causing low pressure. Winds bring water vapour, leading to condensation and rainfall. The winds converge at the ITCZ, a band that forms and changes due to the earth's rotation. Dry air then descends on the Tropics, causing deserts. The whole pattern is called Hadley Cells.

moist season alternate. During the brief wet season, groundwater recharges and vegetation flourishes. Within this climate type, moisture influx varies, supporting agriculture, or pastoralism, or a combination. A minimum of 250 mm annual rainfall is generally needed for farming (Vettera and Rieger 2019). If moisture inflow is smaller than this, animal herding takes over. Savanna ecosystems are crucial in many semi-arid tropical areas, supporting pastoralism that often requires accessing distant water sources. South and Southeast Asia experience a powerful monsoon. On average, the African monsoons bring less rain. In Sub-Saharan Africa and South Asia, 50 per cent of the land is under tropical savanna. Like all other livelihoods in these lands, pastoralism is 'defined by the presence of water sources' in the dry months (Pauline Peteres, cited by Cleaver 1995).

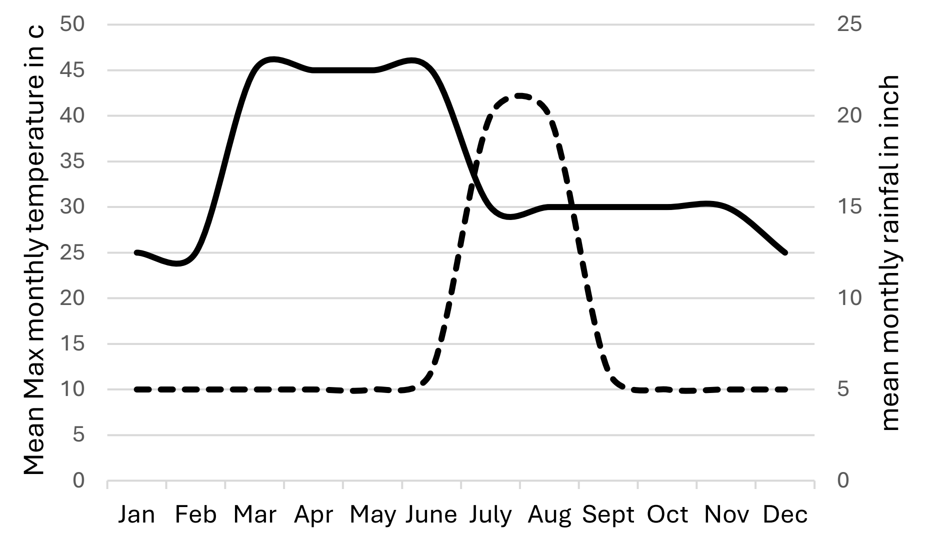
Figure 1 is a stylized representation of the tropical monsoon or semi-arid climate type. Mean monthly rainfall (right axis, broken line) follows a pronounced bell shape. The solid line and left axis show the mean maximum monthly temperature. The question this paper is asking is, what happens to water supply and its seasonal distribution, of which mean monthly rainfall is a significant component when the mean maximum temperature line shifts upwards?

Imagine a temperate zone temperature line that stands below the temperature line in Figure 1 for every month of the year and a mean rainfall in temperate zones that varies in a narrower range than the bell-shaped line shown here. Together these amount to a significantly smaller evapotranspiration rate in the temperate areas. Imagine also an error band around both the lines shown in Figure 1. Actual observations can vary widely around the averages because the pathway of the ITCZ is uneven as well as variable. The climatic zones shown in Map 1 below do not have exactly similar conditions every year and are not even fixed in space.[5]

[5] Global warming could make the definition of where the semi-arid tropics are further unstable. This expansion of the tropics might lead to a conversion of rainforest to pastures or farmlands, a process that seems to have been ongoing in the intertropical regions in Africa, consistent with the

While the picture captures actual data for the Sahel and South Asia well, in some temperate monsoonal regions (northeast Asia), rainfall distribution is relatively even between months. And inter-year variability in rainfall is not as pronounced as in the semi-arid regions. This contrast highlights communities' unique challenges in semi-arid tropical regions, where water management and adaptation to seasonal extremes are crucial for survival and economic development.

Figure 1. Tropical Monsoon Climatic Type



Where is the semi-arid tropic? The Russian-German geographer and meteorologist Wladimir Köppen used temperature values and precipitation volumes as boundaries to classify world climatic zones. This system divided the arid tropics into two main parts: regions with high summer temperatures and seasonal precipitation or monsoon (semi-arid) and regions without significant rainfall. The Köppen classification was first developed in 1884, and since then, it has undergone several modifications. To the extent variability (in rainfall and temperature) is a part of the definition, data collected in recent decades have led to modifications in the classification of some border zones (Peel, Finlayson and McMahon 2007). Other classifications followed in the early twentieth century, by

analysis of https://www.ifpri.org/blog/model-climate-change-greater-threat-tropical-rainforests-cropland-expansion.But this point does not concern the paper.

Charles Warren Thornthwaite, an American climatologist, and the German geographer Carl Troll, proposed alternative ways to capture seasonality; the Troll definition captures the semi-arid type most directly. The Köppen or the Köppen-Geiger system is still robust and remains an essential tool for teaching and research because it is easy to understand.

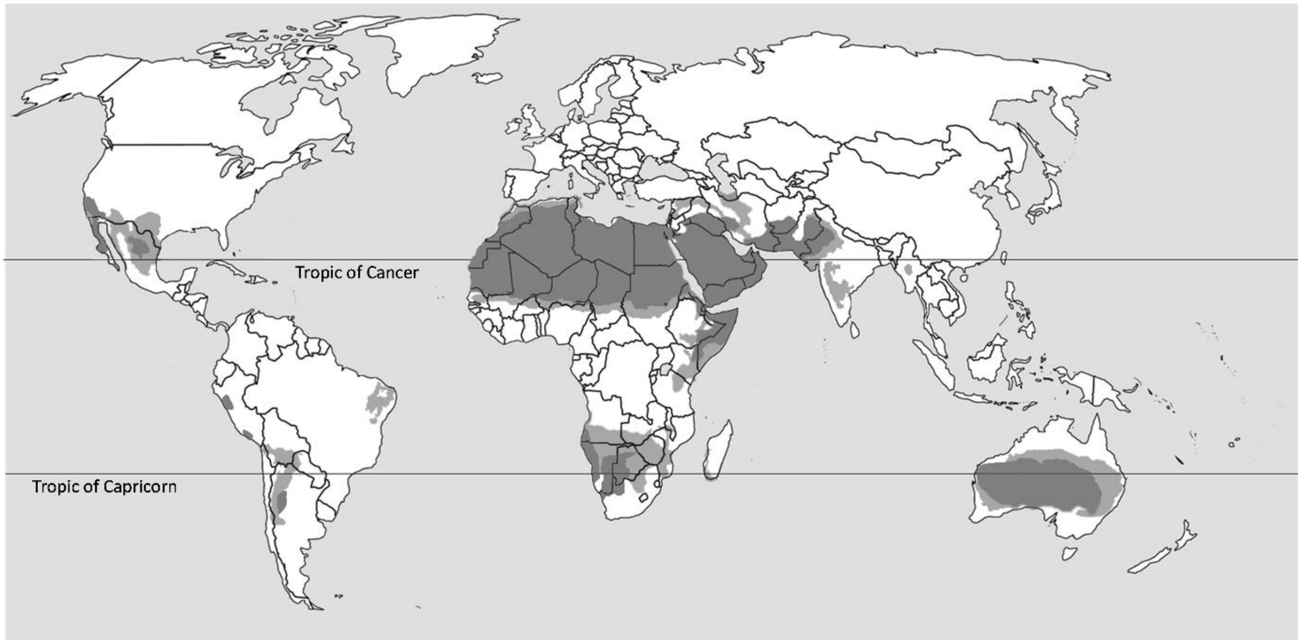
Following the Köppen-Geiger system, the climate type that dominates the earth's surface is B, arid (30.2 per cent), which is almost equally distributed into hyperarid (BWh) and semi-arid (BSh, or arid with some seasonal moisture influx). In Map 1, the areas marked in dark and light grey stand for these two types. The hyperarid is thinly populated, but the semi-arid contains a large, possibly the largest, share of world population between major climatic zones.[6] By drawing a band roughly 700 miles north and 700 miles south of the 23°27′ latitudes, we get the climatic zone identified as the semi-arid or tropical monsoon, in which much of South Asia and the Sahel belong.

Seasonality, of course, exists in most geographies. Tropical seasonality differs from cold climate seasonality in two crucial ways. The really effective mitigation strategy in the tropics must be capital-intensive. In the past, while cold climates required heating through burning wood and coal, arid tropics needed water storage. These strategies were not symmetric due to two key distinctions. First, cold climates generally had higher agricultural yields and fewer famines. Second, while heating homes was achievable with private resources, effective water storage and recycling – effective meaning built on a large enough scale to withstand seasonal evaporation – in the tropics was expensive, requiring collective efforts. Surface water is the cheapest to use and recycle. Dams and drills were not cheap and not available for mass use until recent decades. While

[6] In the northern hemisphere, the major semi-arid tropics (BSh) include India and Pakistan in South Asia; parts of Mali, Chad, Senegal, Niger, Mauritania, Burkina Faso, Nigeria, and Cameroon in West-Central Africa; the Horn of Africa, including parts of Ethiopia and Eritrea; North Africa and the Middle East; the Mexican Northwest; and the southwestern United States. In the southern hemisphere, the semi-arid tropics contain the Australian desert fringe; Kalahari and Namib desert fringe falling in Namibia, Botswana, South Africa, Angola, and southwest Mozambique; Sertão in Brazil; and the southern coast of Madagascar.

seasonality is universal in economic geography, its degree varies depending on the resilience of economic activity to climate in the slack season. Tropical monsoon regions seem to have a much greater difference between the busy and the slack season than Europe or North America. In the 1920s, India experienced interest rate fluctuations 250-300% higher in the busy season compared to the slack season, while the USA saw only a 2-5% difference (US data from Kuznets 1933). The two regions had similar banking systems, their climates differed.

Map 1. Arid tropics, hyper-arid including deserts shown in darker shade, semi-arid in lighter shade



Source: Author, based on Köppen-Geiger data in the public domain.

Figure 1 represents the norm that this paper is more concerned with. However, to establish the norm, it is necessary to talk about significant exceptions. Moisture influx is not the only variable shaping access to water. Also significant are hydraulic conductivity and transmissivity, or how well water transmits over the area, a variable that depends on soil structure and geological formations. Wind patterns and oceans can create microclimates. Five variations are especially important: coastal, mountainous, riparian, groundwater-based, and monsoon-strength-dependent. There are many tropical deserts and near deserts that border the sea.[7] In the past, even in the harshest climates, the seaboard had a better chance to overcome seasonality, sometimes thanks to the more stable flows of a deltaic river and sometimes by trading with the rest of the world, which reduced its dependence on agriculture and pastoralism.

Microclimates in the highlands can sustain a different economy from the plains.[8] Perennial rivers can moderate seasonality. The Blue Nile originates in the equatorial highlands that receive significant quantities of rain throughout the year. Its annual floods enabled intensive agriculture in a hyper-arid strip of land that extended hundreds of miles. The rivers of the Fertile Crescent, fed by snowmelt, carry large volumes of water. In the dry savanna of the Sahel, the Niger Basin created possibilities for intensive agriculture, mixed farming zones, extensive livestock breeding, and commercial fishing. The Indo-Gangetic Basin experiences intense heat but developed agricultural societies because the heat melts Himalayan snow and recharges the Indus and Ganges River systems. Similarly, the eastern Red River Delta sustained agricultural communities in an otherwise dry climate in north-western Vietnam. Against the relentless aridity of the Horn of Africa, strong political centers emerged in the Banadir coast, in the well-watered coastal agrarian belt of Lower Shabelle (and in the cooler uplands in Eritrea and Somaliland).

Lastly, the chances of mining water moderated the effect of climate. In the southwestern drylands of North America and Australia, groundwater resources partly compensated for the high evapotranspiration rates that reduced surface water supplies. Resources underground can matter in other ways. Much of Botswana is very dry; so are the Middle East and North Africa. However, oil and

[7] Western Sahara, North-western Australia, Peruvian and Atacama deserts, Sonora, the Namib, the Middle East, and North Africa.

[8] For example, the Ethiopian plateau did not suffer famines and droughts with the same intensity observed in the desert fringes. Similarly, in precolonial and colonial Eritrea, Namibia, and Madagascar, the political elite lived in the mountains that moderated aridity, whereas much of the surrounding country experienced aridity. Taiwan, through which the Tropic of Cancer passes, has an extensive highland zone. The High Atlas in Morocco moderates the effects of a climate that exposed the planes in the south to droughts.

diamonds create enough export income to combat drought and subsidize vulnerable livelihoods. Finally, the monsoon of the Indian Ocean is powerful and occurs twice. Regions in its pathway – South and Southeast Asia, Taiwan – receive a larger volume of seasonal rainfall than most arid tropics.
A history of response to tropical monsoon conditions is already implicit in the section above. The next section spells it out more fully.

Climate and the economic history of the semi-arid tropics

For centuries, the world's tropical regions have been poorer than the temperate zone countries. In 1992, 'GNP per capita in the tropical regions was 25 per cent of that in the temperate zone' (Sachs 2001). In 1820, GDP per capita in major intertropical regions (South Asia, the Middle East, Sub-Saharan Africa, and Latin America excluding Argentina and Chile) was 30-32 per cent of that in Europe and European settler regions, which had substantial temperate-climate lands.[9] In 1600, the average income in Africa was 47 per cent of that in Western Europe, and in India, 60 per cent of the latter.[10] Only in the late twentieth century was there convergence in average incomes across countries (Bourguignon and Morrison 2002).

This historic poverty of the semi-arid tropics was rooted in climate. The agricultural season was short, and crop choices were limited. The temperature and the high radiation are suitable for vegetation growth, so biodiversity is the greatest in the tropics. However, aridity tends to depress land yield in rainfed farming. The closer one gets to the two tropics, 'production [of food] is limited by insufficient water, for everywhere in the [semi-arid tropics] the annual potential evapotranspiration exceeds rainfall' (Reddy 1983: 843). '[W]ater is a major factor limiting agricultural productivity' (Agnew 1982). Arid areas often have entisols (sandy soil with low organic matter) or aridisols (dry soil with low organic

[9] https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2020?lang=en
[10] http://www.ggdc.net › horizontal-file_02-2010

matter). These soils have low water retention capacity and can support plant growth for a maximum of 90 days without irrigation, usually less.[11] Tropical biodiversity increases the risk of diseases transmitted through environmental pathways (in contrast with human transmission), such as soil, water, vectors, and food sources (Garchitorena et al 2017). City size in semi-arid tropics is limited by the availability of local and perennial water sources. Historically, cities near perennial rivers (e.g., Himalayan rivers) grew larger than those in areas with seasonal water flow.

The relationship between surface water loss and shortfalls in total moisture inflow is more pronounced in semi-arid tropics, increasing the risk of droughts and famines when the rains fail. High drought risk induces risk-averse behaviour, leading to underinvestment and a preference for insurance assets like livestock or gold jewellery. Farmers in semi-arid tropics have preferred indigenous cultivars that provide low but assured yields (Binswanger 1978). Seasonality would have limited the size and capability of premodern states (Karaman and Pamuk 2010 on states data), as they prioritized famine prevention over economic growth (Parthasarathi 2011: 172-5) and struggled to generate sufficient tax revenue. Premodern states found it more challenging to tax herders than farmers. Farmers were no great resource either, for land yield was low. 'With few exceptions, African precolonial states were not very powerful,' even 'essentially fragile' (Roberts 1987: 9-11). European colonizers did not have to try too hard to overcome these fiscally fragile polities.

Seasonality elevated mortality from famines and droughts, depressing population growth rates in Asia and Africa until the early twentieth century. Drought and famine occurred in all geographies. In the tropics, the risk of the combined event was relatively high because, for the same percentage shortfall in

[11] Classifications developed by the US Department of Agriculture. https://www.nrcs.usda.gov/resources/guides-and-instructions/soil-classification

moisture inflow, the semi-arid tropics experience more significant surface water loss.[12]

Although relatively poor, people living in the semi-arid tropics developed response patterns to seasonality. Historically, two main responses to aridity and seasonality in tropical regions were trading in moisture-intensive goods (virtual water trade) and trapping excess moisture during wet seasons for use in dry periods. Examples of virtual trade in water or exchange of goods embodying different water intensities can be found in the trans-Saharan caravan trade and ecological specialization in the middle Niger Basin. Regions also developed interdependencies via non-trade links, including migration prospects during droughts (for example, Baier 1976). Local solutions to seasonality involved trapping runoff and excess rains. Most storages that archaeologists have studied were small in scale, the biggest among them serving a capital city or flood control. Given the limited financial and technological capabilities to build large transregional systems, common responses included circulatory migration, transhumance, and combined herding and farming.

European colonial rule in Asia and Africa, also constrained by small fiscal resources and limited, often misleading, knowledge of geography, still introduced a few significant changes. Partly because they were struggling to raise money, there was often an accent (usually in river basins) on intensive farming and the redefinition of property rights on farmlands. Development plans in areas further away, in savanna and desert fringe, were missing, tentative, or confined to demarking boundaries between pastoral and farmlands. There was an accent on commercial transportation, especially railways. Where railways happened at all, these changed the pattern of virtual trade and arid-moist-zone interdependence.

[12] On average, two severe droughts should occur yearly somewhere in the tropics. Droughts seriously affected nearly two billion people in Asia, Africa, and the Middle East in the twentieth century. The corresponding number in Europe, the Americas, and Oceania was five per cent of that figure, even though the rainfall shortages were often quite similar between these two regions (Below, Grover-Kopec and Dilley 2007).

There was also a significant move made on water infrastructure. With bigger territories under their command, some colonial regimes could imagine basin-wide projects. During colonial times, European settlers and colonial authorities worked on water management in semi-arid regions to promote agricultural development. Attempts to apply European water management techniques to semi-arid environments had mixed results due to environmental, social, and economic factors specific to these regions. However, where there was a permanent water body with plentiful surplus flow during the wet season, efforts to regulate and use that water sometimes succeeded.

In Algeria, French administrators emphasized the need for water security to support colonization efforts, though many projects faced budgetary and ecological constraints (Cutler 2010). In British India, large-scale canal and reservoir projects were implemented, particularly in the South Indian deltas and along the Himalayan rivers. These projects were often responses to droughts and famines, which exposed the weaknesses of imperial rule (Roy 2020). Of these projects, the canal systems in Punjab had a dramatic effect on agriculture and urbanization in the region. However, canal projects also led to waterlogging, salinity, and malaria in some areas. In Egypt (and Sudan), British colonial rule built upon earlier Ottoman efforts to expand commercial agriculture through irrigation, often drawing on lessons learned in India (Shokr 2009). The Office du Niger project in Mali was Initiated by French colonial engineers and aimed to develop land by diverting water from the Niger River (van Beusekom 1997). While the project was scaled down significantly, it remained an important economic base for Mali after independence, particularly during drought and famine.

Similar efforts to combat aridity, river-based or groundwater-based, took off in the US Southwest, Mexico and Australia, from the late nineteenth century. These developments challenged traditional concepts of water rights and property ownership, leading to new legal frameworks. In the interwar period, the construction of multipurpose dams in the US marked a significant shift towards state-funded water projects. Later in the twentieth century, the global spread of dam-building technology would significantly impact agriculture and urbanization in arid regions.

Colonial cities became focal points for water management in the nineteenth century. Urban water infrastructure development was driven by disease prevention concerns and favoured wealthy residents. This led to centralized water systems and improved treatment but also highlighted inequalities between rich and poor, as well as between urban and rural areas. The role of water management in disease control in tropical regions was broader than this field, however. Disease prevalence datasets are not very rich for the nineteenth century, but if Indian trends are representative, then the early colonial rule might have seen a faster spread of epidemics through railways, migration, and the growth of port towns. In the long run, water quality interventions reduced deaths from waterborne diseases like cholera. By 1920, there was a turning point in population growth and life expectancy in South Asia and Africa. Disease control efforts also led to increased livestock populations at the same time.

When colonialism ended in Asia and Africa in the mid-twentieth century, free nations inherited an imbalance between rising population and limited food supply and employment opportunities. That imbalance powerfully shaped thinking on development policy in the 1960s and the 1970s.

In standard accounts of early development thought, accent falls on industrialization. Since the colonial regimes were generally indifferent to industrialization in the colonies, the account overstates the rupture between colonial and national development plans. This is misleading. Water was a more universal preoccupation of new states. And in this field, postcolonial development plans were more deeply influenced by colonial rhetoric and knowledge than historians realize. Colonial knowledge evolved through engagement with climate and environmental challenges. Postcolonial states inherited and built upon this evolving knowledge, and water infrastructure displayed this continuity. The enterprise of damming rivers in poorer countries is often seen as a political project displaying economic nationalist sentiments. While some politicians pursued dams for personal reasons, the practice was rooted in local culture to manage extreme seasonal variations in water flow, supported by advances in hydroengineering, data on seasonal flow, and, from the 1950s, foreign aid. The golden age of dam building began in the 1940s, driven by cheap loans from Western European governments and the World Bank. India embarked on ambitious projects, constructing over a thousand dams between the 1950s and 1970s. Africa followed suit in the 1950s, with major projects on the Nile, Zambezi, and Volta rivers. The 1970s Sahelian drought intensified dam-building efforts.

Generating agricultural transformation by working on the water infrastructure did not always work where trapping seasonal excess was still costly, and the excess quantity was too small to justify the cost. Where it did work, it raised cereal yield and energy production substantially. On the other hand, these projects faced challenges, including rising costs, adverse environmental impacts, and adaptation to drastic changes in water levels (as seen in the Lake Chad projects). Dams and intensive agriculture caused land degradation and changes in disease environments, intensified conflicts between farmers and non-farmland users, and displaced peoples. Despite mixed results, dam construction continued into the 1980s. From that decade, however, multilateral funding dwindled, responding to the mounting criticisms of big dams, and the drive became harder to sustain, though it did not end.

The decline in dam-building led to a shift towards tube wells, supported by state incentives and cheap credit in some cases. Tube-well irrigation surged in India, Pakistan, and Bangladesh, becoming the primary irrigation method by 2010. The groundwater revolution in tropical drylands, such as Australia and northwest Mexico, began at different times and saw significant growth in Mexico in the 1970s due to the green revolution and cheaper deep drilling. This led to agricultural expansion and urban growth but also to over-extraction and inequality. Groundwater extraction often exceeded recharge rates, leading to issues like saltwater intrusion. In South Asia, groundwater use was historically limited to wealthier individuals due to the cost and difficulty of well construction. Alfred Chatterton, an influential Director of Industries in South India around 1910, campaigned for borewells for rural development. It was an expensive technology then. A century later, India had one of the highest densities of wells globally.

The long-term trend shows steeper increases in water access in tropical regions in the second half of the twentieth century than in the temperate areas. Agricultural use of water and urban municipal supply levels per head increased almost everywhere, though the data for most countries covers only the recent decades (which also saw civil wars and the collapse of urban infrastructure in some areas, like Sudan).[13] The income divergence between richer and poorer tropical regions narrowed at the same time. However, it did not disappear, in my analysis because the prospects of sustaining rise in water access were running out.

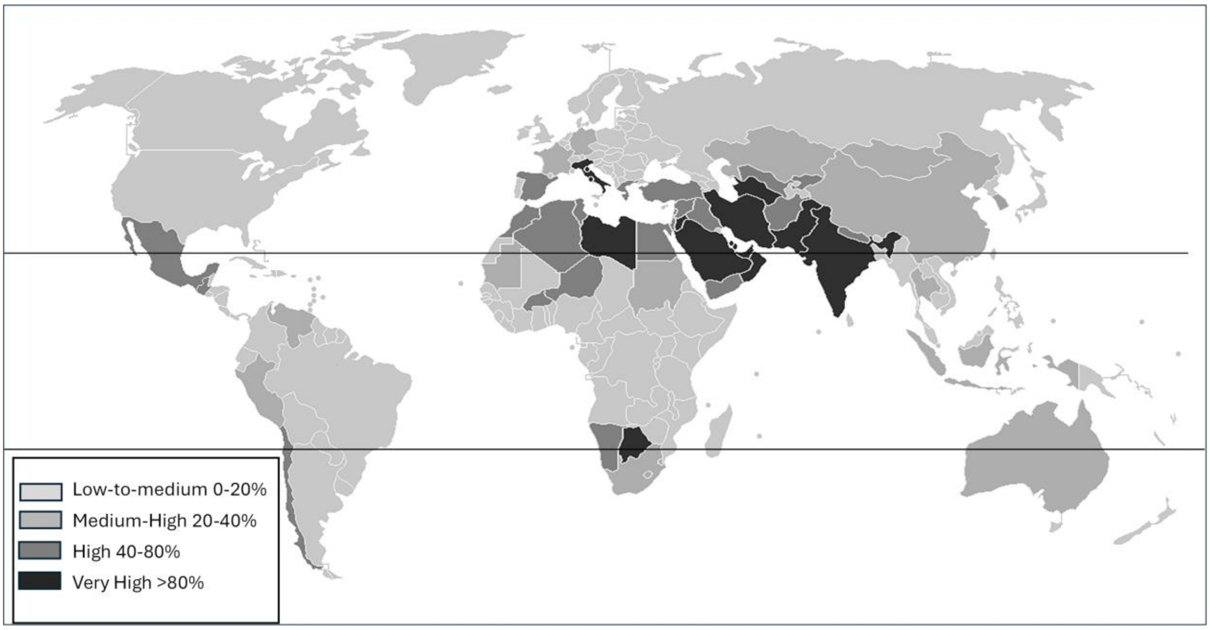
To start with, renewable freshwater is a much scarcer resource in tropical regions, and therefore, withdrawal displays a persistent disparity in water availability across regions, with significant implications for economic development. For example, the Sahel-Sudan region has low land yield, low GDP per capita, and low per capita renewable water (5-30% of the world average). South Asian average falls in the middle range, with about 20% of the world's average renewable water. Water-rich countries like the USA, Canada, and Scandinavia tend to have higher incomes and land yields. In other words, the economic emergence in the tropical regions has been dependent on more intensive exploitation of a particularly scarce resource.

In the 2010s, the withdrawal of freshwater as a percentage of renewable sources touched unsustainably high levels in the semi-arid tropics. A primary measure of water stress is the risk of running out of fresh water. Around 2016, water stress

[13] https://ourworldindata.org/water-use-stress

levels and freshwater withdrawal as a percentage of renewable sources ranged from 42 per cent in India to 105 per cent in Pakistan and similarly high levels in parts of the Sub-Saharan Africa (Map 2). The levels were considerably lower in the temperate countries in Western Europe, North America, Japan, and China.[14] Water stress did not just mean water running out. Modern forms of water control led to a fall in water and soil quality, new inequality in access, and deforestation and desertification. It meant aquifers losing their capacity to recharge. Although underground water can be technically managed as a common property, there is no perfect legal regime that can do this.

Map 2. Water Stress



Source: World Bank data.

Current approaches to managing water stress focus on legal, economic, and technological solutions. Some of these steps deal with water markets and conservation agreements. While some solutions work on small scales, they often face challenges when applied to larger and more diverse populations. Studies

[14] World Resources Institute, https://www.wri.org/resources/charts-graphs/water stress-country.

done in India show that social factors like caste and inequality can undermine cooperative efforts in water management. Legal doctrines governing water use, such as riparian and prior appropriation rights, often prioritize property rights over sustainability. The concept of public trust in water management is, in theory, a way to protect the common sources from which groundwater is drawn, but potentially conflicts with historical entitlements structured around wells above ground.

Among other initiatives in protecting water resources, groundwater recharge and rainwater harvesting are well known, though their long-term impact is yet to be determined. International water trading is feasible, but no large-scale working model currently exists for this concept. Water-conserving appliances for rural and urban use, including overground drips, are cheap and workable. However, drips also fail to deliver results in some of the major grain crops. Cloud seeding and snowpack enhancement are of uncertain impact while being expensive. Desalination is a more promising technology used extensively in oil-rich regions, but it is also energy-intensive.

As this brief overview suggests, in the foreseeable future, the response to water stress in the semi-arid tropics will likely follow the pathway established by the developmental states of the late twentieth century. This pathway involves governments building large-scale infrastructure projects to control and recycle water rather than radical regulation of use, legal remedies to overuse, microtechnology, climate control tools, or reliance on commons management systems.

What might happen to these ways of resourcing water and recycling it if the mean maximum temperature line shifts upward? The section below looks at a current literature on climate and water to answer the question.

How Climate Change Might Impact Water Resources

I cannot claim that the survey is comprehensive. It cannot be because hydrological models are a work in progress, measurements are a work in progress, and there is an ongoing shift from local datasets to global and multilayered datasets.[15] Little of the climate change studies tell us much about tropical water. Like all rapidly developing scholarly fields, modelling climate change suffers from noise and overlaps. On the other hand, economic history does not tell us much or anything about the relationship between climate warming and economic change. We may know what happens when the total volume of moisture rises or falls in an area. There are some historical examples of that. But if seasonality changes, rains come earlier or later, and the rainfall distribution is flatter, steeper, more positively skewed, or negatively skewed; history does not offer many clues on what that might mean for economic activity. Still, Figure 1 helps us distinguish between two scenarios – the precipitation line shifts or the band representing variability shifts. This is useful for me in classifying and interrelating some of the climate change papers.

Let us start with variability. The prediction that 'Global warming is making the atmosphere more hostile to the formation of tropical cyclones,' seems robust enough. [16] This could happen because warming interferes with the convection process, while a rise in sea-surface temperatures and a warmer and moister atmosphere contribute to intensity. Extreme storms become fewer and cover smaller areas as temperatures increase (Ghanghas, Sharma, and Merwade, 2024). Potentially, these are more damaging. The paper, however, is not about cyclones.

Will the average precipitation shift? Climate change will likely impact precipitation in drylands by intensifying rainfall extremes (Rwigi et al. 2024).

[15] For example, hydrological models are sensitive to how the climate variables (like evapotranspiration) are measured.

[16] https://www.scientificamerican.com/article/global-warming-causes-fewer-tropical-cyclones/#:~:text=Global%20warming%20is%20making%20the,Monday%20in%20Nature%20Climate%20Change.

Papers showing streamflow variability in the subcontinental river basins in India has increased since the 1950s (Chuphal and Mishra 2023) support this claim. Soil moisture studies seem to corroborate the finding of greater variability.

Greater openness exists in the prediction of drought occurrence and intensity. Three variables interact to cause a drought: moisture deficit (sometimes measured as soil moisture deficit), unusual warming, and low initial streamflow, or the volume of water in surface waterbodies before the occurrence of a monsoon failure. The first two factors dry up the soil and the plants directly, and by reducing streamflow – the combined prospect is called a meteorological drought. The third factor, baseflow, can counteract the effect to some extent (Singh and Mishra 2024). Consider an environment where warming causes more meteorological droughts but raises baseflow via snowmelt. On the other hand, droughts alter the catchment areas' response to rainfall, potentially impacting streamflow. Arid areas are more sensitive to 'streamflow drought,' but how significant the effect is, remains uncertain (Matano et al 2022).

Will the average shift? Will there be less water or more when aridity rises and seasonal rainfall peaks change in level? Research on permanent shifts in tropical monsoon climatic patterns took off in the 2010s after a 2008 report by IPCC (Intergovernmental Panel on Climate Change). Between 2008 and 2021, many new journals started to publish forecasts and predictions, using more statistical data than before and more capable hydrological models (like MIKE SHE).[17] This enterprise has two limitations. Some of these models assume unchanging parameters, and geographers predict the impact of climate change without factoring in politics and policies to worsen, control, regulate, or reverse the effect. Subject to that limitation, what do these studies say?

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[17] MIKE SHE is a hydrological model created by Système Hydrologique Europeen (SHE) and maintained by the Institute of Hydrology (UK), SOGREAH (France) and DHI (Denmark). There are several other global hydrological models in operation.

The (IPCC) was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization. Since then, the IPCC has periodically gathered scientific data to suggest scenarios for the future that could, in theory, inform policymakers. On water, the IPCC is consistently more negative than hydrological research is. The 2008 assessment report unambiguously predicted climate change will make water scarcer and insecurity (risks) more significant in arid areas. Forecasting precipitation was still at an early stage. The 2021 assessment report marginally revised the claim by adding 'potentially': 'The main climate change contribution to water insecurity is the potential for reduced water availability' (Caretta 2023: 563).

There are five ways hydrological research is not consistent with this strong form of prediction. First, the extent of temperature change cannot be accurately measured until at least 2035. Second, the impact of aridity on human life depends not just on the average rise but also on the variability of month-by-month fluctuations. We do not know enough about how warming or an increase in the average surface temperature affects the variability. Third, the consequences of an average temperature increase for individual regions are difficult to predict. Fourth, while climate change will increase aridity or evapotranspiration, the total effect depends on another variable to which a lot of uncertainty attaches: streamflow (surface water flow fed by all sources). It is impossible to know how streamflow changes in different parts of the world because the hydrological models rely on past data, whereas the causal model may change.

Fifth, there is no agreement on the methodology used to predict the impact of climate change. Using historical data to predict the future is sustained by the assumption of stationarity, meaning the belief that the variability in streamflow stays within observed historical variability. A study to test the robustness of the assumption found (with catchments data from around the world but relatively few from the tropics) that the variability of extreme values associated with floods and droughts did indeed stay largely stationary in catchments exclusively affected by climate change, but not in those where human interventions were extensive (Wang and Yang 2024).

Some local studies predict a definite direction. Despite the disagreements and openness about the link between warming and water stress worldwide, there appears to be enough consensus that arid areas of California and Mexico will see drier conditions by the middle decades of the twenty-first century (Yáñez-Arancibia and Day 2017). Both regions may have some unused underground water. In the arid areas served by a perennial river but with little precipitation, the impact of a rise in aridity or evapotranspiration can be one-directional and less uncertain. Egypt is a significant case. Here, an increase in aridity will likely cause a fall in groundwater levels around mid-century (Eltarabily et al. 2023). But even in Egypt, which has few rainy days in a year, the future depends on how the two sources of the Nile that do get a lot of rain and are both far away from Egypt change.

The health of Lake Chad, a shallow waterbody that changes in size every year and one that sustains the lives of millions of people, is vital for the economic and political well-being of the Sahel. Since the 1970s Sahelian famine, many experts predicted the progressive shrinking of the lake. However, the source of most of its water was not local; it was located several hundred miles to the southeast in the Logon Basin, a semi-equatorial area. According to some estimates, this area is expected to receive shorter bursts of heavier rainfall due to climate change, and no matter the drier conditions in the north, it could still pump more water into the lake (Schmidt and Muggah 2021).

Forecasting streamflow takes place all over the semi-arid tropics. The exercise did not begin recently in response to the prospect of climate change. It started about a hundred years ago when colonial states intervened to deal with seasonality. Forecasts are done by feeding past data into a statistical model, in which some of the main causal variables are precipitation, snow water, and soil moisture. Using such a model, the US Department of Agriculture provides seasonal streamflow forecasts for watersheds across the arid western states. In Africa, the quality of data and modelling vary from country to country. Overall, the density of stations collecting streamflow and weather data is thin compared with the USA, Australia, or India.

One significant byproduct of the forecasting exercise is the hydrological drought index, which measures the shortfall in streamflow from the long-term average. The measures for Africa show that the 1980s saw an almost unbroken episode of hydrological drought like no other registered since the data began to be recorded nearly a century before. In west-central Africa, baseflow (precipitation-led addition to streamflow) decreased from 1950 to 1980, and an increasing trend appeared from 1981 to 2018. In North Africa, the decrease continued (Ayers, Villarini, Tramblay and Kim 2023). Some studies think a declining trend in moisture inflow began decades, even centuries, before anthropogenic climate change became a prospect (Nicholson 2001).

The IPCC's periodic assessment reports permit the broad generalization that the monsoons will be stronger and droughts more intense in the near future. However, whether some semi-arid regions will turn into arid ones or stay semi-arid remains hard to predict because the impact on evapotranspiration and precipitation is not synchronous. It is helpful to examine the measurement in more detail to understand why.

Assessing the impact of climate change begins with two measures: potential evapotranspiration, which reflects the effect of a global temperature increase modified by local factors like types of vegetation, solar radiation, relative humidity, and wind speed; and climate aridity index, the ratio of potential evapotranspiration to actual precipitation. A computation of potential evapotranspiration follows methods developed in the 1940s. The high-resolution global database is a recent addition. The first set of aridity index appeared in 2009. Since then, the data was revised several times. Available from WorldClim, the dataset is a standard basis for building predictions about sustainability, agriculture, pastoralism, and drought risk (Zomer, Xu and Trabuco 2022).

One set of standard measures widely used to predict droughts considers precipitation, leading to at least three criteria: standardized precipitation, standardized precipitation evaporation index or SPEI, calculated as the difference between precipitation and evapotranspiration (which captures temperature or aridity effect), and a refinement of the latter that factors in net evapotranspiration. The aridity index is a variation of SPEI.

The aridity index is an essential tool in human geography. It is widely used to measure the risk of meteorological drought. The greater the index, the greater the risk. There is some openness on where the semi-arid is located between the maximum values of 0 and 1. An index value of around 0.5 indicates a semi-arid state, and an index of 0.8 or above a hyper-arid state. The monsoon rains happen because the amplitude of surface temperature is greater on land than on the sea. An average rise in temperature does not alter that process. In short, a change in potential evapotranspiration may not imply a similar change in the aridity index.

Drought risk depends on short-term changes in precipitation; predictions about such changes carry large margins of error. This is so because, in the northern semi-arid tropics, precipitation is influenced by several climatic systems (Arctic Oscillation, Siberian High, and El-Nino Southern Oscillation). Moreover, the historical correlation between these factors and monsoon strength appears to be changing, making it more difficult to predict short-term changes in monsoon strength even with more data (Xu et al 2023). Existing models predict mean annual rainfall, the spatial spread, and variation in rainfall within a season. The year 1997-98 saw one of the most significant departures in sea surface temperature in recorded history, but the summer monsoon was near-normal in India. Not surprisingly, drought prediction indices offer divergent predictions, and more than one study finds that the aridity index is not a good predictor of drought intensity (Zhang et al 2023).

What about long-term changes in monsoon strength? Considerable research now exists on the future of the South Asian monsoon, and these predictions are reported in IPCC assessments. Comparatively, less research exists for the other semi-arid tropical zones. It is impossible to generalize for specific regions based on South Asia, but South Asia indicates broad tendencies. The South Asian historical data shows a marginal decline in precipitation volume between 1950 and 2000 and a marginal rise after that (Katzenberger, Levermann, Schewe and Pongratz 2022). The IPCC and some scholars attribute this shift to global warming and predict that the northern hemisphere's southwest or summer monsoon is strengthening. That prediction is repeated in blogs, press, and social media writings with added colour. In the short run, more intense monsoons cause floods and landslides. There is some evidence that these problems associated with intensity have aggravated in South and Southeast Asia in the last decade or so. This paper is about the long term. In the semi-arid tropics, the long-term impact of changes in precipitation would depend less on big storms and more on precipitation seasonality. What do we know of seasonality shifts?

A change in seasonality would mean the pattern of crop choices will need to change, and ways to store monsoon runoff will need a rethinking. The climate seasonality index is a measure that combines mean annual rainfall with monthly rainfall. The index moves in a range of 0-1.83. If rainfall is evenly distributed throughout the year, the index becomes zero, and if rainfall is concentrated in one month, the index takes a value of 1.83. A semi-arid seasonality index is typically around 1.2-1.3, suggesting that most rains occur in a two-month window. In the semi-arid monsoon, a rising seasonality combined with increasing aridity might suggest a more pressing need and a more complex challenge to store monsoon runoff. There is a shortage of studies on seasonality. The studies that do exist do not lead to a singular prediction. For example, based on historical data, a study on Western India shows that the seasonality and aridity indexes have risen in recent decades, but the trends are not statistically significant (Rani, Sharma, Babel and Sharma 2022).

As mentioned before, warming and water stress link depends crucially on streamflow. The impact of temperature changes is difficult to reconstruct for riparian regions because both changing monsoon patterns and the El-Niño-Southern Oscillation contribute to river flows directly or indirectly through snowmelt. Warming could cause faster snowmelt and more streamflow, but warming could also lead to smaller snow accumulation and a long-term decline in streamflow. Where streamflow is sourced as snowmelt, climate warming could shift streamflow toward earlier in the year through earlier snowmelt and increased proportional rainfall (Berghuijs and Hale 2024). Using different assumptions about snowmelt leads to the prediction of a basin getting wetter or drier.[18] Most forecasted trends in streamflow are not statistically significant. Paleotemperatures are often not a reliable guide to prediction. Research on this topic seems to be in the preliminary stages, with considerable uncertainty attached to forecasts. The uncertainty stems from, as a study of semi-arid Andean headwaters suggests, insufficient knowledge of snow depth and density over seasons and across space (Navarro, MacDonell and Valois 2023).

A final piece in the puzzle is the relationship between groundwater recharge and increasing climatic aridity. This relationship is non-linear. Recharge rates are disproportionately slower in more arid areas, and recharge is likely to be affected more in arid areas (potential evapotranspiration exceeds precipitation) than in temperate ones. This finding suggests an emerging water inequality between the temperate and heavy-monsoon areas (like Southeast Asia, part of India) on the one hand, where predicted rise in precipitation due to stronger monsoons can lead to proportionately greater recharge potential, and the arid and hyper-arid areas in Africa, India, Australia, and Southwestern United States on the other,

[18] For two studies on the Brahmaputra Basin offering contradictory results, see Alam, Ali, Rahaman and Islam 2021, and Maina et al 2024.

where predicted decrease in precipitation combine with low recharge sensitivity to cause a fall in supply (Berghuijs et al 2024).

Concluding Discussion

The paper investigates how climate change might impact tropical development through changes in resource distribution. The first half of the paper sets out why resources matter to tropical development. The second half explores what we can know about the potential impact of climate change on resource distribution. To do that properly, we need to know what happens to the mean monthly rainfall line if the mean maximum temperature line shifts upwards. On this point, there are some more or less robust results. On the other hand, on snow-fed streamflow and groundwater recharge, two other variables crucial for this exercise, there is less research available. This paper is not concerned with cyclones, floods, and drought intensity, which figure frequently in the media discourses on the tropics but are not very pertinent to tropical development.

We can say three things with some confidence. First, precipitation in the semi-arid tropics is more sensitive to climate change than in the temperate regions because warmer oceans could increase monsoon intensity. Second, it is likely that warming would lead to drier conditions in the rest of the year, with greater evapotranspiration levels. In short, the precipitation line in Figure 1 could be steeper. Third, it is impossible to generalize whether there will be more water in total or less because of this change unless we have better forecasts for groundwater and snowmelt.

This scenario does not call for a fundamental shift in mitigating strategies, or in water recycling and storage technology. However, it potentially makes dry season economic activity more dependent on water and use-related technologies. In short, no radical change in the economic pathway can be envisioned, pending more reliable predictions on streamflow. Whether heat or seasonality levels change, or where they do, the available solutions remain the same—source more water, recycle more between seasons, and deal with the side effects of dams and drills.

One crucial lesson we can draw from these predictions concerns inequality. While technology, especially privately funded ones like a borewell, can raise average living standards, capital-intensity of seasonality-response is inequality-enhancing. In Indian cities, affluent apartment dwellers are more water secure thanks to a borewell than slum dwellers dependent on corporation-supplied piped water from a dam or a lake. More private investment in water technology widens the gap between the rich and the poor. Overall, a rise in technology dependence is likely to create new patterns of inequality in water access and the distribution of water stress.

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