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Article

Indigenous Technology of Terraces and Its Hydrological Functions for Managing Agricultural Water and Addressing Multifaceted Climate and Water-Induced Disasters

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Abstract: Agricultural terraces, an indigenous technology with diverse hydrological functions, play a critical role in agricultural water management and the provision of hydrological ecosystem services. This paper conceptualizes terraces as technological components of a broader agroecological system and examines the underexplored hydrological functions of different terrace types under corresponding agricultural practices. Beyond their primary role in agricultural water management, terraces retard surface runoff, interrupt surface hydrological connectivity, and recharge groundwater. These hydrological processes, in turn, generate downstream benefits such as enhanced baseflows and flood mitigation, thereby contributing to the reduction of multifaceted climate and water-induced disasters. The case study presented in this paper provides preliminary quantitative estimates of these hydrological benefits. Based on these findings, the paper advances three key recommendations. First, it emphasizes the importance of accounting for the hydrological functions of different types of terraces under respective agricultural practices to establish rainfall-runoff-infiltration relationships within terraced landscapes. Second, in light of the increasing trend of terrace abandonment, the paper argues that preventing further abandonment, including the rehabilitation of abandoned terraces, can enhance hydrological ecosystem services, and serve as a viable nature-based solution to address multifaceted climate and water-induced disasters. However, it emphasizes that such strategies should prioritize the establishment of appropriate nature-based agricultural systems, which can simultaneously strengthen hydrological benefits and improve local livelihoods. Finally, from an agricultural perspective, the paper contributes new scientific insights into water control for paddy cultivation on level terraces, an aspect that remains insufficiently represented in conventional engineering-based water management assessments.

Keywords: Agricultural terraces; Paddy and dryland crops; Terrace hydrology; Ecosystem based adaptation; Flood attenuation; Dry season water augmentation; Mid-hills of Nepal

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Introduction

Mountain regions, characterized by large altitudinal variation over short horizontal distances, cover approximately 27% of the Earth's land surface (UN-SD21, 2012). This region plays a critical role in the global hydrological cycle by inducing orographic precipitation, part of which is stored as surface and subsurface reservoirs and later released as dry season baseflow to downstream rivers. The mountain hydrological cycle—comprising precipitation, storage, runoff, and evaporation—is highly complex. Given declining dry-season water availability and increasing wet-season flash floods due to anthropogenic climate change, understanding the mountain hydrological processes is essential for climate adaptation and integrated land and water resource management.

Agricultural terraces, the most striking feature of mountain landscapes, are integral to this hydrological system, as they harvest and conserve rainfall and irrigation water, redistribute it by altering natural hydrological processes, and deliver hydrological ecosystem services and benefits. These terraces are constructed by reshaping hill slopes primarily to control water for agricultural production. Indigenous knowledges, comprising local ingenuity, skills, and techniques, were used to develop them. According to an archaeological study, agricultural terraces were built in China approximately 7,000 years ago to cultivate paddy rice (Yamaoka, 2006). This technology was later spread to other areas in the world, primarily due to population growth and the unavailability of arable land (Wu and Thornes, 1995; Deng et al, 2021). Thus, these terraces are found all over the world, especially in mountainous areas.

Worldwide, in general, two types of terraces, namely levelled with levees and unlevelled, are commonly found although, there exist several subtypes like bench terraces, contour terraces, graded terraces, etc. In most Asian countries, levelled terraces are built for cultivating paddy. Thus, they are also known as paddy terraces.

However, many of these terraces worldwide are either already abandoned or are in the process of abandonment, leading to an overall change in the land use pattern in the hills and mountains (Vincent, 1995; Arnáez et al, 2015; Hussain et al, 2016; Deng et al, 2021). This phenomenon has changed (or is changing) the local hydrological process, further aggravating the ongoing impact of climate change, leading to unanticipated floods and droughts, causing water-induced disaster risks and livelihood threats to the communities living in both the mountain and the adjoining plan areas.

The situation depicted above thus demands appropriate solutions to the livelihood threats to the local community by adopting nature-based solutions that call for an ecosystem-based approach to climate adaptation and sustainable development (Denton et al, 2014; IPCC, 2014; IPCC, 2018). It is understood that such an approach, apart from considering the socioeconomic aspects, intends to deploy indigenous technologies and management practices (IPCC, 2014; UNEP, 2019a; UNEP, 2019b), which makes the technology central to the adaptation process.

In this context, this paper examines the hydrological functions of different types of agricultural terraces, an Indigenous Technology, to examine the extent to which such terraces can address the multifaceted water-induced disasters and meet the agricultural water needs.

Previous studies in terraces and research gaps

It is not to say that agricultural terraces have not been studied. There are piles of studies on terraces. Most of the completed studies on terraces, especially in Nepal, focused mainly on hill slope stabilization, soil and water conservation, and groundwater recharge (Carson et al, 1986; Gill, 1992; SPWP, 1992; Shah, 1993; Tamang, 1994; Wu and Thornes, 1995; DSCWM, 1999; Pandit and Balla, 2004; Shrestha et al, 2018). However, these papers do not analyze hydrological functions of terraces in terms of flood mitigation, baseflow enhancement, and agricultural water management. At the global level (besides Nepal), the existing studies on terraces that are relevant to this paper are of two types. The first set of studies focused on the reviews of terracing (Rogger et al, 2017; Deng et al, 2021). While the second set of studies intended to establish rainfall-runoff-infiltration relationships of terraces through several hydrological models (Gallart et al,1994; Gatot et al, 2001; Kovář et al, 2016; Meliho et al, 2021; Li et al, 2023; Stavi et al, 2024; Deng et al, 2024). Although water control for agricultural water uses is the primary function of these terraces, most model studies have, however, overlooked this function, even though it is responsible for shaping the other hydrological functions of terraces, depending on their types, crops grown in them, and agricultural water management practices. In addition, most of these model studies focused on their respective watersheds with different types of land uses, including terraces in general, without making any distinctions between paddy and sloping terraces and crops grown on them under different water management scenarios, resulting in several types and rates of water ponding and percolation. As a result, the water management functions of these terraces have been overlooked, though these functions are responsible for shaping the other hydrological functions of terraces.

Thus, the hydrological functions of different types of terraces, like flood attenuation, baseflow contribution, water redistribution, and their underlying scientific explanations, under varying agricultural water management practices, are not fully understood for addressing multifaceted water-induced disasters. Such an analysis explaining process-based hydrological or integrative assessment across terrace types and management practices will be invaluable, especially for upland basins (mountainous areas), which have a direct influence on the integrated management of land and water resources for climate adaptation.

The objectives of the paper

The primary objective of this paper is to document and scientifically explain the underexplored hydrological functions of different types of agricultural terraces under varying water management practices, and to assess their contributions to mitigating the multifaceted climate and water-induced disasters. In this context, the paper aims to contribute to conceptual discussions on hydrological ecosystem services by elucidating how terrace typology and management regimes shape hydrological outcomes. The study further aims to inform ecosystem-based climate adaptation policies and to generate new scientific knowledge in agricultural water management that complements conventional engineering-centered approaches.

Material and Methods

This paper draws on multiple field-based studies conducted by the author on Indigenous water management technologies and climate change (Parajuli, 1999; Parajuli and Sharma, 2000; Parajuli et al, 2001; Pradhan et al, 2017; Goes et al, 2017; Parajuli, 2023; Parajuli, 2024). These studies are complemented by focused case studies of agricultural terrace management in the Nuwakot and Syangja Districts, Nepal. In addition, this study, along with the conceptual discussions presented in this paper, draws on an extensive and in-depth review of peer-reviewed literature, policy documents, and technical reports relevant to agricultural terraces and water management in mountainous regions.

Finally, and more importantly, the paper draws on the author's long-term field observations and professional practice in managing and studying irrigated agriculture in mountainous environments in Nepal and other Asian countries.

Results

Agricultural Terraces in Nepal and Their Abandonment

Nepal is predominantly a mountainous country with over 85% of its area covered by hills and mountains. People living in these areas derive their livelihood through subsistence farming characterized by the general integration of crop production in different types of agricultural terraces and livestock raising for animal draught power. Irrigation, by some means in these terraces, is one of the principal inputs for crop cultivation.

In Nepal, two distinct types of terraces exist, locally known as *Khet* and *Bari*. *Khet* is a leveled terrace with levees in it (Figure 1a) where paddy is cultivated under irrigated and flooded conditions in the wet season, followed by the cultivation of wheat, maize, and others during the dry season. Unlike this, *Bari* is a fairly leveled or outward sloping terraces without levees in it (Figure 1b) where rainfed crops like maize, millet, soybean, etc. are grown. However, in some parts of the country (especially in the trans Himalayan regions), leveled and leveed (or bunded) terraces are also used for the cultivation of cereal crops other than flooded rice (Parajuli and Sharma, 2000). This further implies that water control is the primary function of the leveled terraces.

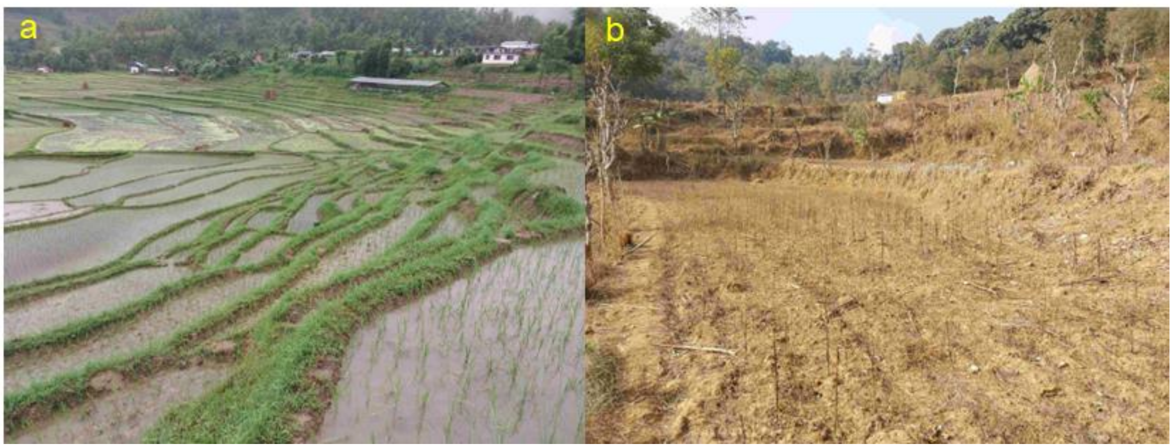

Figure 1: Agricultural terraces. Figure 1a presents levelled terraces, while Figure 1b presents an abandoned fairly levelled (or sloping) terrace originally plowed transversely.

Many of these terraces are either abandoned or in the process of abandonment due to the low returns from agriculture, shortage of labor caused by rural out-migration, and other socio-economic factors (Vincent, 1995; Khanal, 2002; Khanal and Watanabe, 2006; Jaquet et al, 2019; DWRI, 2019). The assessment of land resources in 2019, covering both the mid-hills and mountains, compared to that in 1986, suggested a decrease in the area of agricultural terraces by about 21.3% (DWRI, 2019). This figure is expected to reach approximately 30% by 2025 due to the rapid increase in the abandonment of such terraces in recent years. Figure 2 summarizes the prevailing land use pattern in the mid-hills.

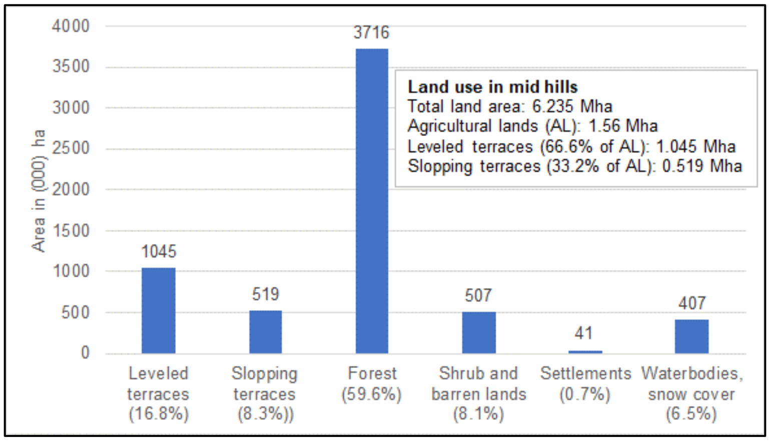

Figure 2: Prevailing land use in the mid-hills (in 000). Source: Annex A, land resources mapping (DWRI, 2019).

It is understood that the abandonment of agricultural terraces in a watershed does influence its local hydrological process and deprives it of its hydrological benefits to a great extent through the changes in land use patterns. However, to what extent the abandonment of agricultural terraces in Nepal has led to the deprivation of hydrological benefits from a watershed is not known, partly due to lack of relevant studies and partly because its impact on the said benefits cannot be segregated from the impacts caused by other factors like climate change, upstream uses of water, and human intrusion in natural resources. Nevertheless, there exists a consensus that, as a combined effect, the peak floods of non-glaciated rivers are increasing, and their dry season flows are declining (CDKN, 2017; WB ADB, 2021; Parajuli, 2023; Aryal et al, 2023). Similarly, several studies have reported a significant decline in the spring discharge or drying up of about 30% of the springs in the mid hills in the last 10 years (Poudel and Duex 2017; Shrestha et al, 2018; WBG 2022). In this context, this paper assesses the extent to which a watershed in Nepal would be deprived of its hydrological benefits due to the abandonment of agricultural terraces in it. Such an assessment would be invaluable for further studies and policy support.

Agricultural Terraces: An Agroecological System and Technology

An agricultural terrace is a manmade agroecological system developed by the local community over the ages using their Indigenous knowledge comprising local ingenuity and skills (Altieri, 1996; Vincent, 1997; Parajuli, 1999). Indigenous knowledge here refers to a cumulative body of knowledge and know-how that has been accumulated across generations by adaptive processes (Nakashima et al, 2018), and it does not solely refer to knowledge generated by Indigenous people.

In a manmade agroecological system noted above, the existing natural landscape is transferred into a terrace with several material objects built in it, water is imported into a location either through rainwater harvest or canal irrigation to change and increase agricultural production, and natural vegetation is replaced by man-developed varieties of crops, and organic manures (compost) are added into the soil to change the prevailing organism-environment setting for increasing agricultural production. In addition, this system provides ecosystem services by altering the natural hydrological process. Figure 3 conceptualizes an agricultural terrace as a manmade agroecological system and technology.

An agricultural terrace is thus a classic example of an agroecological system or an ecological system modified for agriculture through the control of inputs. This concept (agricultural terraces as an agroecological system) helps explain the relationships between manmade congenial environments for crop production, physical elements of terraces, and water-transforming phenomena. In such a system, other than material objects, indigenous knowledge is also central to the continuing performance of these production systems, which implicitly highlights the role of technology.

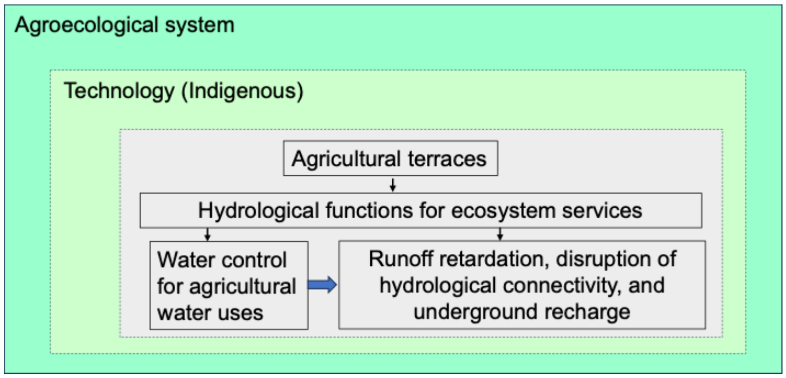

Figure 3: Agricultural terraces as an agroecological system and technology.

Agricultural Terraces: An Indigenous Technology

Technology, in general, refers to the capacity to transform goods into desired things (Vincent, 1997). In engineering water management, technology is a system consisting of a material object that can transform water from one level to another for a desired output through a process that is governed by natural science. Such objects, when created using Indigenous knowledge, are termed Indigenous technologies.

In this sense, an agricultural terrace consisting of material objects like a lower side levee, plow pans, and overflow spillway, etc., in levelled terraces, and transversal plowing and terrace riser ditch in the sloping terraces, that help harvest, conserve, and transform water primarily for agricultural production and other hydrological ecosystem services, is a technology. The said transformation involves a complex process governed by science, which is caused by the interaction between several social and technical parameters. Some such social parameters are the social infrastructure of rules and procedures, the people, and their multiple activities. Likewise, the technical parameters include the types of terraces, crops, and their water requirements, soil types and their physical properties, availability of water, geology beneath the terraces, etc.

Thus, an agricultural terrace, other than a classic example of an agroecological system, is also an indigenous technology developed by the local community for managing (or controlling) water for agricultural production.

Agricultural Terraces and Their Hydrological Functions

Agricultural terraces contribute greatly to ecosystem services (as hydrological benefits) through several hydrological functions, which are not yet fully understood. The four key functions are: managing or controlling water for agricultural uses, runoff retardation, interrupting the hydrological connectivity of surface runoff, and groundwater recharge. The sections below describe these hydrological functions.

A. Water control for agricultural water uses

The hydrological functions of a terrace for controlling water for agricultural water uses are shaped by the types of terraces (sloping and leveled), which are described below.

Sloping terraces (Bari)

Sloping terraces are usually plowed transversely to allow the formation of small ridges across the slope (Figure 1b) for intercepting the surface runoff during rain events and conserving the same underneath the soil for their later use by the crops. Part of such water seeps into the groundwater reservoir (Figure 7) to meet the other hydrological functions. In this context, based on the field-based experiment, Tiwari et al (2009) noted that such terraces with reduced tillage operation for cultivating dryland crops in the Dhadhig District, Nepal, could reduce the surface runoffs of the major rain events, amounting to 16-70 mm in 24 hours, by 6.7 to 11.3% compared with the general landscape around. The average slope of the terraces was 11-12%, while the average annual rainfall recorded during the three-year study periods was 1202 mm. Likewise, the reduction of rain-induced surface runoff by agricultural terraces in China (with an average annual rainfall of 550 to 900 mm) varied between 4.6 and 21.5% (Deng et al, 2021).

It is not easy to compute and compare the quantum of water running off the plot as a percentage of the total volume of water entering it from rainfall (termed as the runoff coefficient), because the runoff characteristics of each terrace vary greatly depending on the way it is managed. However, Gardner and Gerrard (2003), in general, noted that a group of terraces conserves an average of over 50% of individual rainfall events.

The information depicted above clearly suggests that, besides the soil type and rainfall intensity, the hydrology of sloped terraces (runoff and infiltration characteristics) is greatly influenced by the way terraces are managed (plowing and tillage) for cultivating crops of different types (cereals, fruit trees, vegetables, etc.).

Levelled terraces (Khet)

Leveled terraces are usually built with levees and are cultivated primarily under irrigated conditions. Figure 4a presents the physical configuration of such a terrace with its key hydrological components.

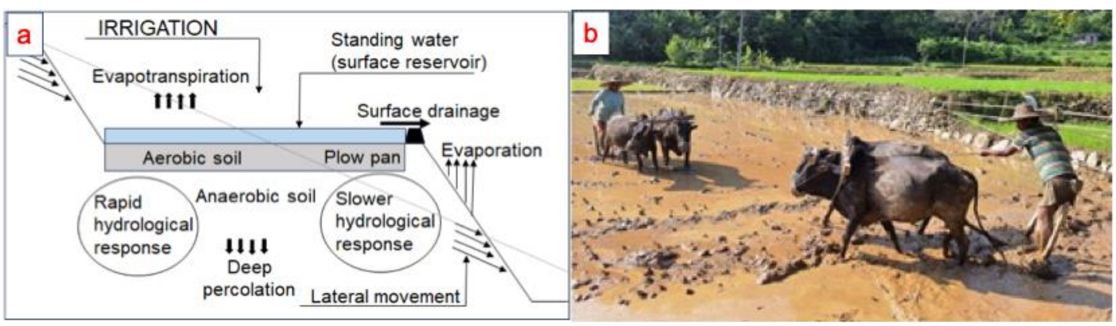

Figure 4: (a) Levelled terrace, water movements, and (b) puddling the soil.

When the standing water is to be maintained on a terrace for cultivating paddy, a plow pan is created underneath by puddling the soil. Puddling is the process in which the soil mass is stirred and leveled simultaneously by plowing and harrowing it under standing water (Figure 4b) to dissolve its granular structures and thereby form a soft layer of soil known as the "plow pan" to reduce its hydraulic conductivity, sometimes termed as permeability. Permeability is one of the important engineering properties that defines how fast water seeps through the given soil. This process reduces water percolation through the plow pan, creating an anaerobic condition therein, which is essential for paddy cultivation. This is because paddy roots absorb more nutrients from the subsoil under anaerobic conditions. In addition, this process helps the microorganisms to decompose the available organic matter in the soil, parts of which are consumed by the plant roots as nutrients, and the other parts (toxic) are leached through their eluviation and illuviation (Koga, 1992). Referring to an example of an alluvial fan in central Japan where paddy yield tends to increase with a decrease in the rate of percolation amounting to 15-20 mm per day, Koga (1992) further noted that there exists a strong relationship between the paddy yield and rate of percolation, indicating the importance of the puddling process to achieve an intended rate of percolation.

An analysis of the measured data in the 4 paddy plots in the Sankhar Irrigation System, Nepal, also suggested a similar yield-percolation relationship (Parajuli, 1999). This system was operating under rotational irrigation, with 55 hours of rotation, with an average stream size of 6-8 lps for cultivating early paddy. The dominant soil type in this system consists of loam to clay loam, locally known as rato mato. As a result, farmers in this area intensively puddle land for paddy transplantation to increase its water-retaining capacity. Figure 5 presents the average rate of percolation of standing water through the plow pans of 4 plots of paddy field for the critical growing periods and the corresponding yields of paddy. As noted by Koga (1992), this figure also indicates a certain relationship between the rate of percolation through the plow pans and the corresponding yield of paddy. Initially, the rate of percolation in all four plots remained between 15.3 and 28.8 mm per day. However, after 21 days of the paddy transplantation, the plow pan of plot 2 cracked, and the standing water could not be maintained therein as the rate of percolation through the cracked plow pan was excessive. As a result, plot 2 could not remain under anaerobic conditions, and the paddy yield reduced to 1.19 t/ha compared to paddy yields of 2.69, 3.15, and 4.3 t/ha in plots 1, 3, and 4, respectively (Figure 5). In such a situation, if the plow pan of the paddy field cracks during the early stage of paddy transplantation, farmers usually uproot paddy seedlings, the field is re-puddled, and the same seedlings are re-transplanted. It is learned that such re-transplanted seedlings yield more than the normal paddy if continuous submergence in the paddy field is maintained.

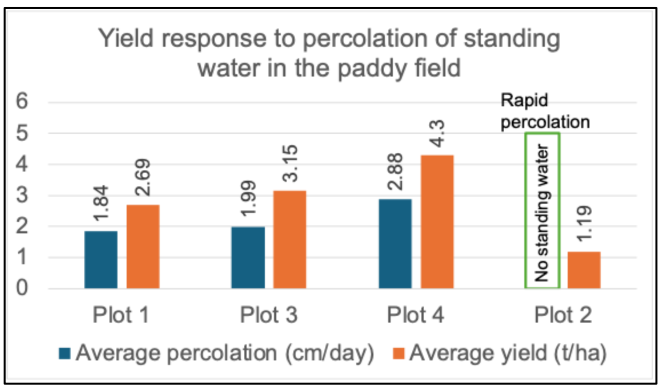

Figure 5: Water percolation through plow pans and paddy yields. Source (data): Parajuli (1999).

The rate of percolation from the paddy field is also shaped by the mode of irrigation. Under continuous irrigation, percolation loss tends to be low (Yoder, 1986; Parajuli, 1999). This is because, under continuous mode of irrigation, the plow pans always remain wet, and chances of developing hairpin cracks in them, which intensify percolation losses, will be minimized.

The situations depicted above explain how complex agricultural water management is for cultivating paddy in leveled terraces. It thus involves coordinated management of water in terms of managing its supply and demands, maintaining terraces and the plow pan for creating a congenial environment for the plant roots to absorb nutrients from the soil, and to minimize water losses through it. Of the several types of water losses, percolation, evapotranspiration from crop coverage, overflow from a terrace, and evaporation from terrace risers are the main ones (Figure 4a).

Although the existing engineering and agronomic procedure recognizes most of these losses in assessing water requirements for cultivating paddy in hill terraces (PDSP, 1990; FAO, 1992; Jacob, 1995), it fails to acknowledge the water losses through evaporation from the terrace riser, particularly due to a lack of knowledge on the micro-hydrology of a terrace. As a result, the engineering assessment of water losses through deep percolation, estimated to be about 10-20 mm per day (Jacob, 1995), is far less than the actual requirement, blaming farmers for using more water in practice. In addition, the yield response to the percolation loss of water in a paddy field is also not understood and accounted for in engineering water management.

B. Runoff retardation

One of the main hydrological functions of paddy terraces is to retard or delay the runoff for flood attenuation. Acting like a reservoir-like entity of a series of interconnected cascaded paddy terraces (Figure 6), it accumulates rainfall over its surfaces and then redistributes it by reducing and retarding the runoff and then lowering the peak flow in the river downstream (Figure 6). The quantum of runoff redistribution and its rate of retardation are, however, shaped by the local contexts, especially the pre-storm water levels in terraces, their levee heights, and storm intensity. A rough estimate suggests that a terrace with a levee height of about 15 -20 cm can easily retain a storm size of 100 to 150 mm/day before the water overflows through it.

In Nepalese hills, terrace levees are usually planted with short-planted legumes partly to strengthen the levees and partly for intercropping. In addition, at a specific location, a hard surface spillway, usually made up of flat stone, is built over the levee to escape the excess water. Thus, the amount of water a terrace can hold during a storm is shaped by the design of levees and their structural stability. In this context, a rough estimate suggests that a terrace with a levee height of about 15 -20 cm in Nepalese hills can easily retain a storm size of 100 to 150 mm in a day before the water overflows through it.

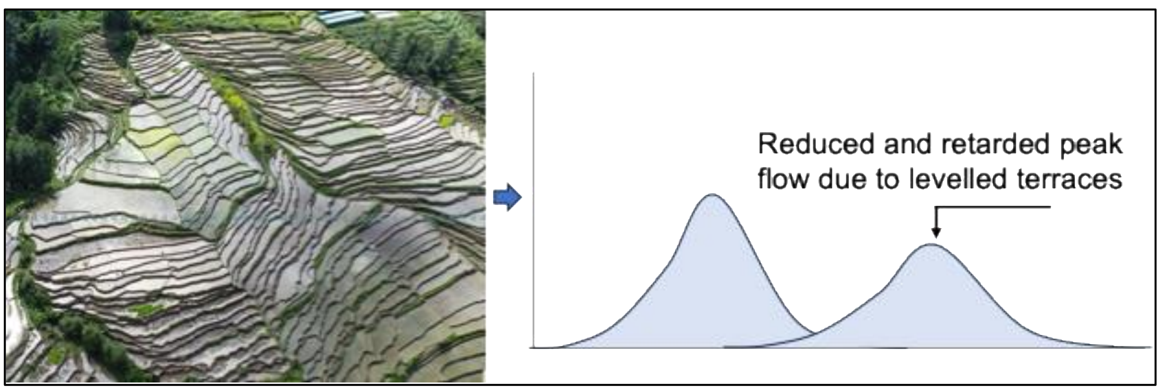

Figure 6: Runoff redistribution for flood attenuation.

Studies conducted in Deharadhun, India (subhumid climate), Tam Duong, Vietnam (average annual rainfall 1435 mm), and the Loess Plateau, China (semi-arid continental monsoon climate) suggested that the terraces in these countries did reduce the field level runoff by 80, 75, and 87%, respectively (Deng et al, 2021).

C. Disruption of hydrological connectivity

The hydrological disconnectivity of rain-induced surface runoffs due to interruption of their flow path, as noted in Figure 7, compared to naturally sloped terrain, is one of the hydrological phenomena of the cascaded dryland terraces (leveled or sloped). This phenomenon increases the rate of infiltration into the soil and subsequently reduces the surface runoff, making the peak flow in the river downstream less peaky.

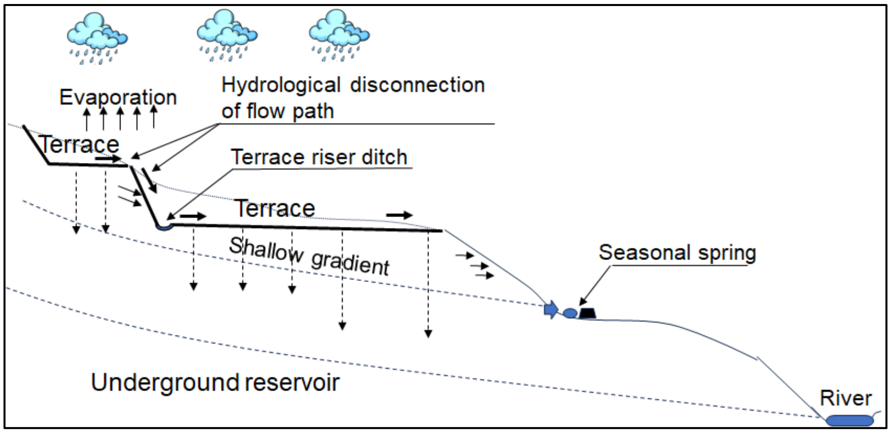

Figure 7: Subsurface flow.

It is to be noted that most of the sloped terraces (*Bari*) in Nepalese hills are built with terrace riser ditches on their hillside (Figure 7), partly to control the watering (during rain events) of the dryland crops being cultivated in terraces, and partly to collect and drain the excess water toward the side drain for their use further downstream. This is certainly an innovative example of indigenous technology adopted by local communities to interrupt hydrological connectivity and transfer it towards the desired direction.

Several studies conducted mostly in the Mediterranean countries and a couple of countries in Asia have documented such a hydrological phenomenon of dryland cascaded agricultural terraces that reduce the run-off contribution of the areas by about 30 to 60% (Meerkerk et al, 2009; Arnáez et al, 2015; Deng et al, 2021). Although specific studies on the disruption of hydrological connectivity in Nepalese hills are not available, Gardner and Gerrard (2003), based on several other studies, noted that a good proportion of the rainfall (probably 50–70%) infiltrates into the soil in such a cascaded dryland terrace.

D. Subsurface flow for groundwater recharge

As noted above, subsurface flow underneath both the levelled and sloping agricultural terraces (*Khet* and *Bari*) is one of the key hydrological phenomena. In general, water that seeps into the ground gets stored therein as a subsurface reservoir. However, due to the complex hydrological features of mountains, the gradient of such flow is shaped by patchy hydrological characteristics of the area depending on its terrain, geology, soil types, and hydrostatic conditions. Usually, part of the water that infiltrates from agricultural terraces seeps down to the groundwater reservoir, which ultimately feeds the waterbodies downstream, including rivers and springs. While part of it, especially in the wet season, flows along its shallow gradient and spouts in the air in the form of seasonal springs (Figure 7).

Seasonal springs are localized in nature. These springs spout in the air along the natural depression, mainly during the onset of the monsoon season (July–August), and continue flowing for a few months. Their discharges are supported by the patchy hydrology of mountainous environments. Numerous such springs are found in the hills and mountains, which greatly contribute to the local agricultural systems and domestic needs for water. Box 1 presents an example of such a spring.

Box 1: Patchy hydrology of agricultural terraces and seasonal springs

The Sankahr Irrigation System in Syanga District irrigates 37 ha of terraced lands belonging to 112 farmers. The Keladi River, a perennial stream with a watershed of about 6 sq km, is the main water source for irrigation. A network of canals (main, branches, distributaries, and field channels) supplies water to its command areas. The irrigated area, consisting of an elevated but gently sloped terrain with terraces (locally known as *tar*), is dissected by a few natural depressions. Shortly after the cultivation of monsoon paddy in the upper terraces, a few seasonal springs spout in the air in these depressions. Waters from two such springs are accounted for managing the system as a whole, which are channeled back to the main system through the adjoining distributary canals for irrigating lands downstream. These springs continue flowing even after harvesting the monsoon paddy.

Although the quantum of water that a subsurface reservoir of the agricultural terrace can contribute to the waterbody downstream is shaped by the local context, studies conducted in paddy terraces in Korea and Japan suggested that about 55 to 75% of the water that infiltrates the subsurface reservoir ultimately joins the springs and river downstream (Hur et al, 2006; Yamaoka, 2006).

Discussion

The mountain region contributes to the global hydrological process, especially in triggering orographic precipitation, storing it in various forms, and releasing the freshwater to water bodies downstream for several uses. The agricultural terraces play an important role in this process and greatly support the statement "mountains are water towers for the plains". Besides managing water for agriculture as their principal function, these terraces provide several ecosystem services as hydrological benefits through harvesting and conserving water. Two such hydrological benefits, which are the concerns of this paper, are flood attenuation and water augmentation.

Although agricultural terraces have provided these hydrological benefits for ages, such benefits are now declining due to the continuing terrace abandonment. This phenomenon not only reduced the agricultural productivity of the area but also aggravated the impacts of climate change, supporting incidents like instantaneous peak floods and reduced stream and spring flows downstream, threatening the livelihoods of the local community, including women and children.

As the climate is changing, and because of its location in the Hindu Kush-Himalayan region, where the rate of warming has increased at a faster rate over the last five decades against the global average that varies between 0.1 and 0.3 °C (average 0.2 °C) per decade (IPCC 2013; IPCC 2018; WMO 2024), climate change–induced threats to Nepal and other countries around are experiencing a higher level of threats compared to the rest of the world (CDKN, 2017; Wester et al, 2019; WBG, 2022), which will get worse in the coming days (Wester et al, 2019), there is a need to explore ecosystem-based solutions to climate adaptation to minimize the water-induced disaster risks to the local communities in Nepal.

In this context, reviving agricultural terraces (or converting the sloped barren lands into terraces) in the mid-hills and mountains could be one of the nature-based solutions for climate adaptation. The section below first discusses to what extent these agricultural terraces could enhance the said hydrological benefits, with some preliminary quantitative indications of such benefits, followed by a discussion on the likely strategy for reviving these terraces.

Agricultural terraces for flood attenuation

The three hydrological phenomena of agricultural terraces described above, namely the reservoir-like entity of cascaded paddy terraces, reduced hydrological connectivity of runoff flow-path along the hill slope, and reduced runoff coefficient of terraces, delay the downstream passage of runoff and simultaneously reduce its volume, leading to attenuation of river flood downstream. Of these phenomena, the hydrological phenomenon of the cascaded paddy terrace is the main one.

It is to be noted that several areas in Vietnam, China, and India have experienced a runoff reduction of about 80% due to paddy field terraces in those areas (Deng et al, 2021). Such specific studies are not available in Nepal.

However, in considering the prevailing land use pattern of Nepal as reflected in Figure 2 and adopting the runoff coefficient of 80% as noted above, a preliminary runoff estimation with Nepal's monsoonal climate suggests that the peak flood of a non-glaciated stream, with a watershed area of about 1,000 ha containing 16.8% of paddy terraces (Figure 2), would be reduced by 13. 4% compared to a situation of no paddy terraces. This estimation will further increase if the contributions to the runoff retardation due to the reduced connectivity of the runoff flow path and the reduced runoff coefficient of dryland terraces are accounted for. It is worth noting here that in this analysis, the round figure of 1,000 ha has been selected to quantitatively assess the preliminary relationship between the watershed area and its hydrological benefits.

Agricultural terraces for water augmentation

Paddy terraces in the mid-hills usually remain under standing water for at least two-thirds of the paddy growing period, through which water percolates. Based on the reported percolation rate of 12.7 to 64.8 mm per day (Wu and Thornes, 1995) and the data presented in Figure 5 above, the average percolation rate from the paddy field would be about 30 mm/day. With these considerations, a preliminary assessment suggests that 4.0 million cubic meters of water percolate through paddy terraces comprising 16.8% of the watershed area (Figure 2) of 1,000 ha. This estimation further increases when the contribution from the spring season paddy terraces is also accounted for.

In addition, quite some rainfall during the rainy season infiltrates the sloping terraces (*Bari*) due to their transversal plowing and reduced hydrological connectivity of the runoff flow paths. Considering that a cascaded agricultural terrace (*Bari*) can infiltrate over 50% of the rainfall (Gardner and Gerrard, 2003), a preliminary estimation suggests that such terraces covering about 8.3% of the watershed area of about 1000 ha would infiltrate about 0.5 million m^3 of water from an annual rainfall of about 1200 mm. In adding this figure to the infiltration from paddy terraces, the total quantum of infiltration during the monsoon season will amount to about 4.5 million m^3. In assuming that half of this water would reach the waterbodies downstream (Hur et al, 2006; Yamaoka, 2006), agricultural terraces covering 25.1% (16.8 leveled and 8.3 sloping terraces) of the watershed area of about 1000 ha could contribute a flow rate of about 71 liters per second to waterbodies downstream. These quantitative data on water augmentation, however, are derived following the preliminary scenario-based estimates.

Suggested strategy for reviving agricultural terraces

The above preliminary assessments advice that reviving the abandoned agricultural terraces or converting the barren lands into terraces will enhance the availability of water in springs and rivers, and at the same time help attenuate the peak river floods downstream. This paper, however, suggests that simply reviving the agricultural terraces would not generate such benefits unless the appropriate agricultural systems are put in place. To this end, this paper argues that understanding the functions of several types of terraces in terms of water control for agricultural uses and hydrological services, including their interrelationship, is thus essential before trying to revive them. This is because it is the agricultural system that shapes the hydrological functions and subsequently the benefits of these terraces.

Thus, the strategy should first focus on: How can these terraces be put back in place for agricultural activities that promote nature-based irrigated agriculture? As paddy fields contribute substantially to the intended hydrological benefits compared to the sloping terraces, priorities should first be given to producing Indigenous varieties of paddy. Some such varieties in Nepalese hills are: Jumli Marshi, Anadi Ric, Pokhreli Masino, Manbhog Rice, etc. Their unique flavor, nutritional benefits, and distinctive taste, followed by farming them organically, will make their cultivation economically viable. Further, exporting such indigenous verieties of paddy (rice) can also be regarded as virtual trading of water. Other likely crops are cost-effective horticulture, agroforestry as green infrastructure (Forest Research, 2022), medicinal plants, and other similar crops.

Irrespective of the crops to be grown, commercial or cooperative farming, preferably under an integrated approach, that provides substantial employment opportunities to the young generation, should be the priority rather than the subsistence farming being practiced these days. Once these terraces are put back in place for the said agricultural activities, their other hydrological functions and subsequently benefits in terms of flood attenuation and enhancement of dry-season flows would follow accordingly.

The hydrological benefits depicted above not only support the farming communities but will also support the urban communities downstream. Thus, the resources required for the said agricultural development, including physical intervention where required (revising terraces and developing new ones), may be generated by introducing a "green climate adaptation fee". Such fees may be introduced to water providers for urban users, water-led industries, hydropower producers, and so on. Fortunately, Nepal has immense potential for developing hydropower. The Hydropower Development Plan of Nepal proposes to initiate the development of 156 hydropower projects with an installed capacity of about 25,610 MW by 2050 (WECS, 2024) from among the 443 hydropower projects. This requires an investment of about US$63 billion by 2050, and the benefits are said to be attractive. A fraction of such benefits may be invested in reviving terraces, as these hydropower plants will be among the main beneficiaries of the aforementioned hydrological benefits.

However, the physical intervention on terraces where required should be guided by guidelines that blend modern sciences with indigenous technologies and knowledge base. Keyline plowing (Giambastiani et al, 2023), inward-sloping terraces, and trenches beneath the terrace risers are some examples of indigenous technologies.

Limitations

Although several studies have examined agricultural terraces in Nepal, they do not provide their rainfall-runoff-infiltration relationships. Consequently, the quantitative estimates of hydrological benefits of agricultural terraces presented in this paper are preliminary, as they are derived from limited spot measurements and secondary data.

Needs for future studies

Although several studies worldwide have attempted to establish the relationships between these terraces and their hydrological benefits, most of the studies have overlooked their agricultural water control function, which is responsible for their other hydrological benefits. In addition, most of these studies focused on terraces in general, without considering specific hydrological functions of terraces of different types.

Thus, the hydrological functions of different types of terraces under different agricultural practices (irrigated or rainfed) need to be duly taken into account in developing relationships between agricultural terraces and their hydrological benefits. As such relationships are site-specific and nonlinear, studies should be conducted in several mountainous regions, including Nepal.

Conclusions and Recommendations

There is a broad consensus that mountain regions function as water towers for downstream plains, and the findings of this study provide empirical support for this understanding by demonstrating the hydrological significance of agricultural terraces. The paper examined the agricultural and hydrological functions of agricultural terraces, an indigenous technology developed approximately 7000 years ago. While agricultural water control remains their primary function, terraces also perform important secondary hydrological functions such as runoff retardation, interruption to the hydrological connectivity of surface runoff, and groundwater recharge, which together generate significant hydrological ecosystem services.

This paper demonstrated that water control for paddy cultivation under anaerobic conditions involves complex hydrological processes and associated soil-water management systems that are inadequately captured in conventional engineering-based water management practices. Factors such as yield response to percolation losses through puddled clayey soils and evaporation losses from terrace risers are often overlooked. Consequently, actual water use for paddy cultivation in the hill and mountain regions is significantly higher than engineering-based estimates of crop water requirements. Improved understanding of these underlying hydrological processes is therefore essential for more efficient management of increasingly scarce water resources.

This paper further highlights that the other three hydrological functions of agricultural terraces (runoff redistribution, interruption to hydrological connectivity of surface runoff, and groundwater recharge) that have been providing critical ecosystem services in terms of flood attenuation and augmentation of dry season flows to water bodies downstream need greater attention in the context of prevailing climate change. This is because rapid and widespread abandonment of agricultural terraces in the hill and mountain regions has led to the decline of these ecosystem services, thereby exacerbating climate-related impacts such as flash flooding and reduced stream and spring flows downstream.

Although estimating precise quantitative relationships between agricultural terraces and hydrological ecosystem services is challenging due to strong local contextual influences, the preliminary scenario-based estimates presented in this paper provide useful numerical indications. The analysis suggests that a watershed of approximately 1000 ha, with 16.8% of its area under paddy terraces, could reduce flooding by about 13.4% compared to a scenario without paddy terraces. Similarly, the same watershed with an additional 8.3% of its area under sloping terraces could contribute approximately 71 liters per second of additional dry-season flow to waterbodies downstream.

While these estimates are illustrative and vary across locations, they underscore the hydrological significance of agricultural terraces in delivering ecosystem services. Accordingly, this paper emphasizes the need for systematic studies across diverse agroecological regions to better understand terrace–hydrology relationships, explicitly accounting for different terrace types and agricultural management practices.

Finally, the paper argues that strategies to address climate change impacts through the revival of abandoned agricultural terraces and the conversion of barren lands into terraces should prioritize the establishment of appropriate nature-based commercial agriculture systems. Such systems can simultaneously enhance hydrological benefits in terms of flood attenuation and augmentation of dry season flows to water bodies downstream and enhance local livelihoods. In this regard, the introduction of a "green climate adaptation fee" at local and national levels could facilitate the institutionalization of such ecosystem-based adaptation pathways.

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