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Water, Energy, Food, and Ecosystem (W-E-F-E) Nexus River Basin Policy Paradigm for Agriculture Transformation and Multisector Infrastructure Development of Nepal

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Abstract

Water is Nepal's most abundant resource, and its development and utilization are essential for driving the development of multisector infrastructures (agriculture, energy, industry, urban development, etc.). Nepal has hitherto adopted an isolated and sectoral silo policy approach to development planning that has remained the dominant mode of planning across many countries in the world with few exceptions until recently when inadequacies of sectoral planning became apparent. The search for alternatively more integrative approaches came into the forefront of development discourse in the backdrop of shrinking natural resources, climate change, inexorable demand of a rapidly growing urban population, and other needs and requirements at a global scale.

The river basin-wide W-E-F-E nexus development policy strategy offers significant potential for optimum water resource utilization driving development of all sectors, including agriculture. The fundamental aspect of the W-E-F-E nexus policy framework entails the understanding of interdependencies and interactions amidst its components (water, energy, food, and ecosystem) and assessing their synergistic impacts on food, energy, water, and environmental securities in the basin. The W-E-F-E nexus policy framework aims to harness the synergy created from the interaction of interlinked components to achieve sustainable development goals (SDGs). This paper argues that Nepal government must carefully weigh the pros and cons of designing singular run-of-river mega hydro-project visa-vis multipurpose water reservoir projects with provisions of integrating irrigation, drinking water, inland waterways, and flood control infrastructures besides hydro-energy leveraging W-E-F-E nexus relationship.

Keywords: Integrated River Basin Development, Multipurpose Development Projects, Sustainable Development Goals (SDGs), TBM Technology, WEFE Nexus Policy Paradigm

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1. Introduction

This paper emphasizes the importance of the Water-Energy-Food-Ecosystem (W-E-F-E) nexus as an integrated planning policy framework for natural resource development in achieving water, energy, food, and ecosystem security that ensures sustainable development goals (SDGs). The paper argues that the W–E–F-E nexus as an integrated river basin development policy framework is highly imperative to address the need for integrated development of developing countries whose economies are primarily dependent on natural resources (water, land, forest, and agriculture). Unless the W-E-F-E nexus becomes the dominant planning framework that replaces the existing sectoral planning framework in general and the sectoral water resource development in particular, economic prosperity and sustainable development goals (SDGs) cannot be realized. Developing countries cannot ignore the W-E-F-E nexus planning framework to meet the growing needs of water, energy, food, and ecosystem service security of their people as well as the sustainability of the natural resource base for future generations (Pandey, 2017; Upreti et al., 2022; Upreti, 2021). The W-E-F-E nexus policy framework is critically important for Nepal because water is the most precious resource available that must be utilized judiciously, with the integration of the development of hydropower, irrigation, drinking water, inland waterways, flood mitigation infrastructures, and human and industrial consumptions.

Agriculture transformation in Nepal can be achieved by developing adequate irrigation infrastructures and utilizing water and energy judiciously. This will increase food production by many folds, and subsequently enhance the ability of the farming communities to safeguard and manage the natural resource base (Shrestha et al., 2018; Upreti et al., 2022). The crucial question is which approach to adopt for developing water resources in Nepal that can integrate, connect, and drive the development of other sectors, such as energy, agriculture, urban centre (drinking water), tourism and industrial development. Specifically, what planning policy and development strategy can prioritize water as the central element and drive the interconnected development of sectors intertwined with water resources? This paper argues that multipurpose water reservoir development projects conceptualized within the W-E-F-E nexus framework, can contribute significantly to yield better results due to the synergy and resource use efficiency created by the W-E-F-E nexus and, thus, needs to be adopted as a national development planning paradigm.

2. State of Agriculture

Despite its tremendous development potential, Nepal is still considered one of the world's poorest. Agriculture currently contributes only about 26 % to the GDP, despite employing 60 % of the population. Ideally, this should have been the opposite, with agriculture employing 20-25 % population and contributing 50-55 % to the GDP. Nepal used to export grains four decades ago, but now it is importing grains and agricultural products worth more than 1200 million USD annually from neighbouring countries (Upreti, 2022; Bhattarai et al., 2020).

The productivity of agricultural labour in Nepal is significantly low, estimated at only one-fourth of the productivity of the overall economy. The major cause of low agricultural labour productivity is the subsistence type of agriculture and the fact that the most productive labour force (those in the 20 to 40 age group) seek employment abroad or in other sectors within the country. Another critical factor hindering agriculture growth is the virtual absence of the agro-based business sector which is directly connected to the productivity and growth of agriculture in neighbouring countries like India and Bangladesh. Small and medium-sized farmers in these countries have benefited from agro-industries, and agriculture has become a profitable enterprise for them.

Given Nepal's limited per capita arable land, the promotion of agro-based business sectors increased agricultural productivity through the development of irrigation, energy, input (fertilizers, improved seeds, cold storage etc.), and market infrastructures is essential for making agriculture economically and sustainably profitable. Shortage of farm workforce and climate change and its adverse impact effect is also posing serious threats. Climate change will have serious impacts on water bodies, particularly mountain glaciers, river waters, and surface and subsurface water quantity and balance in the river basins.

Year-round irrigation is the most important determinant for the transformation of subsistence agriculture into commercial one. Without adequate irrigation water, the potential of other essential inputs, such as fertilizers, improved seeds etc. cannot fully be realized, and the productivity of agriculture remains stagnant. National agriculture development policy must prioritize the commercialization of agriculture in Terai, as Terai has the largest chunk of prime arable agriculture land (1.6 million hectares). Table 1 exhibits, out of 1.6 million hectares, not even 50 % (.6 million hectares) of the land has accessible year-round irrigation infrastructure. Most of these lands are partially irrigated and heavily dependent on the monsoon water causing low productivity. Another 50 % of irrigable arable land (.8 million hectares) is completely devoid of irrigation water and a hundred percent dependent on the monsoon. Even if 50 % of Terai arable agriculture land is brought under year-round irrigation, this will not only increase the agriculture productivity by 2.5 to 3 times but also lays the foundation for the commercialization of agriculture in Terai (Upreti et al., 2022).

Table 1. Irrigated and potentially irrigable land in Nepal

Category	Terai		Hills		Mountains		Total, ha ('000)
	ha ('000)	%	ha ('000)	%	ha ('000)	%	
Cultivated agricultural land	1,594	44.8	1,566	44.0	401	11.3	3,561
Potentially irrigable land	1,480	65.3	627	27.7	159	7	2,265
Present area irrigated							
Surface water	434		170		41		654
Conjunctive use	207		–		–		207
Groundwater	226		8				234
Total	866	79.8	178	16.4	41	3.8	1085
Remaining potentially irrigable land	613	51.4	448	38.5	118	10.1	1180

Source Adapted from Irrigation Master Plan (2019)

There is an ample amount of sub-surface water available in Terai for year-round irrigation of 0.6 million hectares of irrigable arable land through electricity-powered tube wells. The total electricity required for the year-round irrigation of nearly 0.6 million hectares has been estimated to be about 300 MW (Shrestha, 2018). If the required electricity is made available to the farmers at subsidized rates, the increased agriculture productivity will not only ensures food security but also generates nearly $2.5 billion in revenue (Upreti et al., 2022; Shrestha, 2018).

Water constitutes a pivotal resource element for a diverse range of activities including but not limited to irrigation, hydropower, and human and industrial consumptive uses. Nepal must judiciously plan water utilization and development prudently, avoiding a singular focus on hydro-energy generation that compromises its multifaceted benefits.

3. Water Resource Development Policy Review

Let us briefly revisit the current water resource development approach in Nepal and the development policies and strategies guiding it. In reality, there is no well-conceived national policy or strategy for water resource development. Instead, it is based on adhocism motivated by political interest, bureaucrats, and special interest groups to control and exploit the country's critical rivers for the sole purpose of generating hydropower. The current water resource development policy has completely disregarded the holistic approach of integrating energy, irrigation, drinking water, industrial, and other varied consumptive uses. In Nepal, there is virtually no inter-ministerial involvement, coordination or interaction when it comes to water resource development. The Irrigation Department has been moved back and forth between the Ministry of Agriculture and the Ministry of Energy and Water Resources depending upon the government's interest and convenience rather than professional and functional requirements. Consequently, there is virtually no coordinated involvement and efforts among these stakeholders, departments, and ministries in the development and implementation of energy, irrigation, drinking water, and other water-related projects, often leading to a lack of understanding of each other's work.

Development of irrigation and drinking water infrastructures in the hydropower reservoir development project can irrigate thousands of hectares of agricultural lands and supply water to urban centers with relatively less capital investment, significantly increasing the food production in the country and meeting drinking water and other consumptive and industrial uses. This will undoubtedly encourage the farming community to participate in watershed and environmental management. The adverse climate change impacts reinforce the need for an integrated, holistic development policy paradigm in the development of Nepal. The Water, Energy, Food, and Ecosystem (W-E-F-E) nexus policy strategy offers the greatest potential for the integrated development of water, energy, food, and the maintenance of ecosystem processes in the river basins to achieve Nepal's economic prosperity and sustainable development goals (SDGs).

4. Water–Energy–Food–Ecosystem (W-E-F-E) Nexus Policy Paradigm

There is no universally agreed definition of the nexus approach among development professionals. However, they seem to agree to concur on the nexus as a concept that describes the linking of these components (W-E-F-E) and serves to understand the interdependent relationship among them. Hoff (2011) was the first development professional to describe the water-energy-food nexus approach, which focuses on achieving water, energy, and food security in an emerging green economy of the world and aims to leverage higher resource use efficiency of the nexus. The nexus, thus conceived, reduces tradeoffs, builds synergies, and increases water, energy, and food security, which ultimately results in securing access for all people. The nexus concept was founded upon the principle of sustainability and was adopted by all participating states at the first UN Conference on Sustainable Development in Rio.

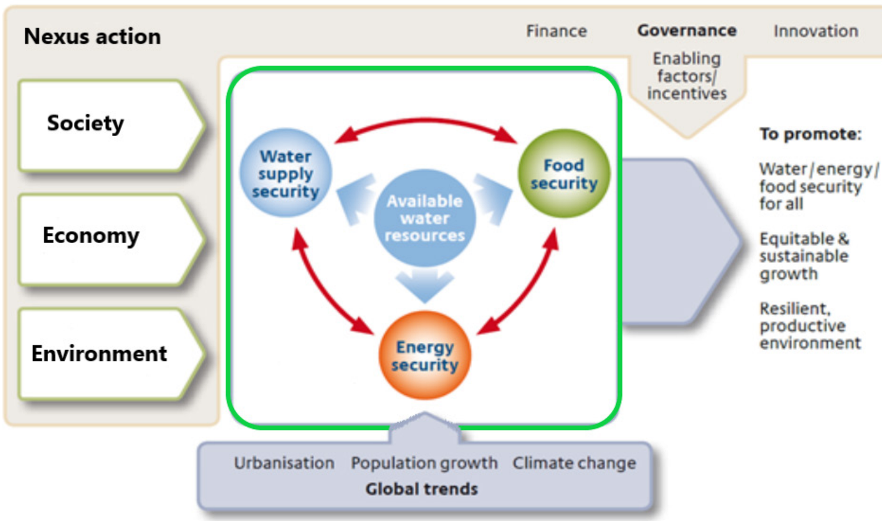

Fig 1: Water, Energy and Food Nexus (Source: Hoff (2011))

Thus, the W-E-F nexus concept serves as a framework for analyzing the dynamic interdependent relationship among water, energy, food, and ecosystem to achieve equitable distribution of these services. Recently, the ecosystem component has emerged as an integral part of the nexus due to the dynamic impact of the ecosystem on other components of the nexus. Moreover, under certain conditions, ecosystem services can hold even greater importance. Hence, ecosystem services have been added to the nexus framework to account for their interdependent relationship with other components. (ICIMOD, 2021; Upreti, 2022). Environmental thinkers, and now international communities have long recognized the interconnection and interdependence of the water, energy, food, and ecosystem components and require an integrated policy planning approach to address the escalating global challenges of securing water, energy, and food security while maintaining the ecosystem health and achieving SDGs (Goodland, 1988; Costanza, 1991; Upreti, 1994; Upreti, 2022). W-E-F-E nexus components are interconnected and deeply intertwined, and their mutually enabling interactions form the basis of sustainable development. It is in this context, the W-E-F-E nexus policy approach becomes paramount in addressing the adverse effects of climate change and maintaining the productive capacities and resilience of interlinked nexus components (water, energy, food, and ecosystem health). The policy decisions inferred from the W-E-F-E nexus paradigm provide optimism for mitigating the adverse effect of climate change, human adaptation, and economic, environmental, and social sustainability ultimately achieving water, energy, food, and ecosystem security for human well-being.

5. Water Resource Development Beyond Hydropower

Water is a precious resource that is essential for sustaining life, ecosystem processes, and human social and economic infrastructures, including energy, agriculture, and industrial systems. Its numerous uses, including irrigation and food production, energy generation, domestic consumption and sanitation, transportation, industry, ecosystem processes, and recreation, have a significant impact on the need for integrated development of this resource, especially given its growing scarcity worldwide. The development and management of water resource projects for integrated multiple uses undoubtedly yield multifold benefits compared to development for a singular purpose like hydropower or irrigation.

Furthermore, the complex interaction among different elements, such as water, energy, food, and ecosystem in a nexus relation, makes it critical to evolve an integrated approach to water resource development that can harness the synergies from the positive interactions among them. Water is the central component in this interconnected network of W-E-F-E elements, essential for irrigation for food production, hydropower generation, direct human consumption and industrial uses, ecosystem functioning, etc. As the world's population grows, urbanizes and demands more food and energy production, water for human and industrial consumption, and maintenance of ecosystem processes, it is necessary to understand the intricate relationships among these intertwined components and develop policy strategies and approaches that leverage the synergy created by their interactions to yield multiple benefits.

A multipurpose hydropower reservoir project that leverages the W-E-F-E nexus framework is the most rational approach to developing Nepal's water resources, agriculture, energy, and maintaining ecosystem processes. However, a major challenge in such projects is sharing the benefits among stakeholders and competing users. The SHARE concept and the principles as outlined by Branche (2017) provide essential guidelines for sustainable development and management of multipurpose hydropower reservoirs involving the participation of all stakeholders in river basins, ensuring more sustainable and equitable outcomes. Endo et al. (2017) note that simulation and optimization management models can provide valuable insights into the tradeoffs inherent in the W-E-F-E nexus relationship, and guide scarce resource allocation over time to maximize the overall welfare of the societies.

6. Why River Basin W-E-F-E Nexus Planning Policy for Nepal?

Nepal is primarily a country of three major river basins:, Koshi, Narayani and Karnali. with many sub-basins within each primary river basin. Table 3 shows the relative distribution of land and population between the basins, with Koshi having about one-third of the land area and 50% of the population, mainly due to the Kathmandu Valley being located within the basin. The Narayani basin is about 25% of the land area and population, and the Karnali Basin is about 42% of the land area and 23% of the population. Therefore, the river basins and their sub-basins play a vital role in Nepal's socio-economic development.

Table 2: Major River Basins

Basin	Area(km2)	Population(M)	Districts(#)	Sub-basins(#)
Karnali	62,299	6.10	25	4
Narayani	38,749	6.58	22	2
Koshi	46,742	13.81	30	5
Total	147,790	26.49	77	11

Source: Irrigation Master Plan 2019

According to MoEWRI (2020), more than 225 billion cubic meters (BCM) of surface water is available every year in Nepal that can be used for the generation of much-needed hydropower and the development of irrigation, drinking water, and other infrastructures for multisector development including agriculture transformation. However, due to the non-uniform temporal and spatial distribution of the water resources, less than 10% of available water has been utilized in the country for irrigating agricultural lands (MoEWRI, 2020). The generation of hydro-energy in the river basin and the development of irrigation infrastructures to leverage the abundant available water resources provides the foundation not only for agricultural revolution but also the multisector development for achieving the economic and social prosperity of the country. Moreover, agriculture's contribution to Nepal's gross domestic product (GDP) can be increased by many folds, making agriculture a game changer in the country's development.

The W-E-F-E nexus framework is a fundamental aspect of understanding the interdependencies and interactions among the components and how their interactions impact food, water, energy and environmental securities. Increased availability of water causes the corresponding abundance of hydro-energy and vice versa because energy can extract water from the sub-surface and move water bodies from one river basin to another across landscapes (using TBM technology), and can be used for a vast number of operations such as inland waterways and transportation, flood control, fisheries, human consumption (drinking), and agriculture-related heating and cooling systems, etc. This intricate nexus relationship among these resources did not come to the surface in the development planning framework of most countries in the past. Very recently, the W-E-F-E nexus evolved to its prominence in policy and development discourses in the light of global environmental problems exacerbated by climate change and rapidly increased demand for human consumption (Upreti et al., 2022; Scott et al., 2015; Simpson & Jewitt, 2019).

The hydrology of Nepal's river systems is driven by monsoons during which the water volume in the major river systems increases by manyfold and is drastically reduced during the dry season. The collection of monsoon water by designing multipurpose water storage reservoirs is the most promising and rewarding act of water resource development in Nepal from the perspective of multiple uses of water for generating hydro-energy, irrigating arable lands during the dry season, water supply to urban centres, mitigating floods and developing inland waterways, fisheries, and tourism development. Multipurpose integrated water reservoir hydropower projects in river basins can generate many additional and even better benefits, enhancing water, energy, food, and ecosystem security against climate risks, drought, floods, and increased connectivity with inland waterways and navigation (Biswas & Tortajada, 2001; Tortajada, 2014). Nepal's river systems contribute half of the annual flow of the Ganges and 75 % during the lean, dry season of March to May (Pun, 2004). Jeuland et al. (2013) report that Nepal stores less than 1 % of the total annual runoff since there are no water reservoirs in the major river basins of Nepal. However, more than 30 sites have been identified as suitable for building multipurpose water reservoirs with a capacity of 121 KM3, which is equivalent to 18 % of the total annual flow of the Ganges (Biswas, 2008). Nepal occupies the central position in the Hindu-Kush Himalayan (HKH) range. Water, energy, food, and environmental security are inseparably connected to the rivers originating from the Himalayas, which provide huge potential for the development of water resources for hydropower, irrigation, fisheries, flood mitigation, inland waterways, navigation, and tourism (de Fraiture et al., 2010; Rahaman, 2009; World Bank, 2014).

Currently, many hydropower projects are under construction in Nepal to meet increasing energy demand within the country and export surplus energy to neighbouring countries to reduce the trade deficit Nepal is facing with India. These projects are designed to exclusively generate electricity compromising many potential benefits for both upstream and downstream riparian populations within major river basins of Nepal. Such run-of-the-river hydropower projects cannot meet electricity demand due to the drastically reduced quantity of water during the dry season when more energy is needed and have virtually no other benefits for people living in the river basins. This approach to water resource development cannot meet the growing demand for water, energy, food, and other competing uses and also compromises the development of other potential better benefits.

6.1 W-E-F-E - and multipurpose hydropower reservoirs

Hydro energy is the largest renewable energy source in the world and currently has more than a million MW (1085 GW) installed, producing 3200 TWh/year energy. This is only 16 % of the total electricity generated worldwide, of which 76 % of electricity is renewable (ICOLD, 2017). Dams store water for different uses and requirements. About 56 % of the world's dams are built for a single purpose, and irrigation is the most common use, and about 44 % of world dams are built for multipurpose, including hydropower generation (ICOLD, 2017). Most of the dams built for irrigation purposes have the possibility for additional energy generation. The potential appeal of such solutions is demonstrated by the case of the USA where more than 80,000 non-powered dams have been detected with a total potential of an additional 12 GW (Hadjerioua et al., 2012).

Multipurpose hydropower reservoir projects can be designed in Nepal's major river basins integrating irrigation and drinking water infrastructures from which water can be transported from one place to another within and across river basins to irrigate thousands of hectares of arable agriculture lands. Hydro-energy generated can be used to establish fertilizer manufacturing plants, post-harvest cold storage facilities, and agro-based industries. Water can be used to recharge and maintain surface and sub-surface water balance and maintain ecosystem services of the landscapes. The circular movement of the water, energy, food, and ecosystem services can maintain and enhance each other's productivity, and water remains the central component of this circularity.

If hydropower projects are designed with a singular objective of generating hydro-energy, this will critically constrain Nepal's development opportunity because it would be impossible to convert such projects into multiple-use projects and the multiple benefits that could have been generated would be forgone. Nepal government's current foreign direct investment (FDI) scheme encourages foreign companies to invest in hydro-energy generation, which is faulty and suicidal for Nepal's long-term water resource development because such a scheme will not have the provision for the development of multiple-use infrastructures and gives the total control of the river water to the investor companies exclusively for a hydro-energy generation. From the perspective of private investors, a single-purpose hydropower project naturally, financially, and operationally becomes more attractive, but the such scheme does not allow the full realization of the multiple benefits and synergies obtained from designing the multipurpose hydropower reservoir infrastructures. It is possible to develop an investment scheme with public-private partnerships for the development of multipurpose hydropower infrastructure projects and make it attractive from the inception of the design phase with the involvement of the government to resolve issues arising from conflict of interests among different uses.

6.2 Monsson water and multipurpose water reservoirs

As table 3 indicates, six South Asian countries have a total hydropower potential of around 388 GW of which only 16 % of this potential has been utilized. For the realization of this potential, South Asian countries, in general, and Nepal, in particular, require building multipurpose water storage reservoirs infrastructures to capture monsoon water to generate hydropower, irrigate arable lands, supply water to varied consumptive uses, develop inland waterways, mitigate flood, develop fisheries, and tourism infrastructures. The collection of the monsoon water is extremely important because the distribution of the water is highly skewed as 80 % of the total rainfall occurs in four months from June to September and quickly flows to the sea, drastically reducing hydro-energy generation from the run-of-the-river hydropower projects in the dry season (January to May). With multipurpose water reservoirs, water can be released in the dry-lean season, ensuring the full potential of hydropower generation, and generating multiple co-benefits including irrigation for food production, water supply to urban and industrial sectors, mitigation of drought, fisheries development etc.

Table 3: Hydropower Potential in South Asia

Potential	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Total
Theoretical potential (MW)	23,000	755	30,000	184,700	80,000	100,000	388,006
Feasible potential (MW)	23,000	755	24,000	84,004	43,000	59,000	236,350
Installed (MW)	442	230	1615	51,756	867	7,320	62,230
Current utilization (%)	1.9	30.4	5.3	28	1.1	7.3	16

Source: Bergner (2013) and International Hydropower Association (2017).

The rivers originated from HKH range in general, and Nepal's rivers, in particular, are highly susceptible to the strong seasonality resulting in low dry-seasonal flow in the river basins. The dynamics of Nepal's river systems are driven by the monsoon, which dramatically increases the risk of climatic and hydrological drought in the dry season. This calls for the necessity of designing and building multipurpose hydropower reservoirs to harvest monsoon water and supply water during the dry season, ensuring the generation of a constant higher quantity of hydro-energy and water supply for various consumptive uses, including irrigation, substantially mitigating the hydrological drought and climate risk during the dry season. The water released in the dry season from multipurpose hydropower reservoirs can meet many essential needs apart from hydro-energy and irrigation, drinking water in urban centres and industrial uses, etc. Studies suggest that multipurpose hydropower reservoirs can be built upstream to capture monsoon water and augment river flow during the dry season, mitigating water stress and meeting many essential needs (World Bank, 2014; Wu et al., 2013; Rahaman, 2009).

Nepal's hydropower projects are run-of-the-river projects from which electricity generated is drastically reduced in the dry season, during which more energy is needed for domestic, industrial and irrigation purposes. Such projects cannot harness the potential multiple benefits and undermine the realization of such benefits with negative effects on public goods and services. From multipurpose projects designed leveraging the W-E-F-E nexus, water used for generating hydropower can be utilized for irrigating agricultural land downstream, developing navigation, fisheries, tourism, mitigating floods, and improving connectivity. The multipurpose function of the water reservoir dams should first be considered in the design phase so that potential multiple benefits from such reservoirs can be harvested and are not foregone forever. Nepal cannot afford to continue the current sectoral approach to water resource development and must adopt the holistic, integrated W-E-F-E nexus policy framework as a development policy planning paradigm. If Nepal continues its water resource development with the singular objective of generating electricity, such an approach precludes the opportunity of receiving multiple benefits and the optimum uses of natural resources sustainably to achieve SDGs in the context of the ever-increasing shrinking of natural resources (water, energy, biodiversity, and ecosystem services).

7. W-E-F-E Nexus and Agriculture Infrastructure

The availability of more than 225 billion cubic meters of surface water is something that can rarely be found elsewhere in the world given the physical size of the country. This huge amount of water can be used to generate much-needed hydro-energy and irrigation infrastructures and increase agricultural productivity. Multipurpose water reservoir projects (MWRP) designed from the W-E-F-E policy paradigm can have many direct and indirect circular impacts and implications on the construction and creation of agriculture-related infrastructures in the country. These infrastructures constitute the very basis for the rapid transformation and commercialization of agriculture. Some of these infrastructures are briefly described below.

7.1 Irrigation infrastructures

It is apparent that Nepal's agriculture suffers miserably from inadequate irrigation throughout the year despite having abundant water resources in the country. Perhaps, there is no other country in the world that faces such an unfortunate predicament. One of the most important benefits of MWRP, apart from hydro-energy generation, is the construction of irrigation and water transport infrastructure from the reservoir site to the area where it is needed for agriculture, drinking purpose, and other consumptive uses within and across the river basin. The use of modern Tunnel Boring Machine (TBM) technology in Nepal has already proved that it is feasible to transport water from an area of water abundance to an area of water scarcity in a mountainous country like Nepal (Upreti, 2022). Hydropower energy generated from MWRP can be utilized to transport water from low land to upland (lift irrigation) for meeting irrigation and drinking water requirements of the communities living in the mountains and valleys. Likewise, hydro-energy can be made available to the farmers in Terai Madesh at a subsidized rate to irrigate about eight hundred thousand hectares of highly irrigable but unirrigated agriculture lands through the tube wells utilizing available sub-surface water. Nepal's agriculture is predominantly monsoon dependent (approx. 75% of arable land), which can only partially irrigate the limited arable lands annually. Until we find an alternative for monsoon-dependent agriculture and food production systems in Nepal with the development of adequate year-round irrigation infrastructures, the future of Nepal's agriculture, food production, and food security will always remain an enigma. Furthermore, Nepal's development depends on agricultural development due to its multiplier effects on other sectors, including agro-based industries, cottage industries, tourism, and energy development (Upreti, 2022).

The government of Nepal (GON) recently intensified the much-awaited Kaligandaki Tinau Diversion Multipurpose Project (KTDMP). The KTDMP project will divert 90.6 cubic feet of Kaligandaki waters per second from Ramdighat in Syanja district to the Tinau River in Rupandehi district through a 9-meter wide and 30 km-long tunnel (myRepublica, 2021). The multipurpose project envisages irrigating 107,000 hectares of land (54,000 in Kapilvastu and 53,000 in Rupandehi) and producing 126 MW of electricity (Gautam 2021). Nepal cannot achieve prosperity without an environmentally sustainable Green Revolution which is possible only through a water-energy-food nexus development strategy that can integrate water resources, hydro-energy, irrigation infrastructures, and drinking water.

7.2 Fertilizer manufacturing infrastructures

The farmers of Nepal have been chronically suffering from the government's utter neglect and lack of political commitment to make essential agriculture inputs, particularly fertilizers and improved seeds, available to the farmers at a critical time when they need them. The availability of major chemical fertilizers (N-P-K) at a critical time of the farming season has been an ongoing saga for the last 30-35 years, even after the advent of democracy and the dissolution of the Panchayat system. According to MOA, the annual need for chemical fertilizers has been reported to be around 0.8 million metric tons at a far less recommended dose for three major food grains (rice, wheat, and maize). With increased year-round irrigation and commercialization, the fertilizer requirements will increase at least by 2.5 to 3 times (2 to 2.5 million tons).

It makes no sense to talk about the commercialization of agriculture without the timely availability of agricultural inputs, particularly fertilizers and improved seeds. Voices and concerns have been raised in the past and the present for the establishment of a fertilizer manufacturing plant, and political parties have been parroting their commitments for a long time but always ended up with the entanglement of commission scandals. A well-equipped fertilizer manufacturing plant requires around 500 MW of electricity which is huge by any standard, but now the situation has changed. In the next 3-4 years, Nepal will have 2500–3000 MW of hydro-energy and allocation of 500 MW to the establishment of a fertilizer plant should not be a problem.

7.3 Post-harvest cold storage infrastructures

There is not even a single cold storage infrastructure in the country. Perishable agriculture products, particularly vegetables, fruits, dairy products, meats, and other commodities, can be kept intact and preserved in cold storage warehouse facility for 3-4 months from the time of harvest. This is considerably significant length of time during which high-value perishable agricultural products can be safely stored and translocated to regional, national, and international markets through the development of an efficient supply chain marketing network. With cold storage facilities, and well-planned commercial production of vegetables and fruits in temperate, subtropical, and tropical regions, dairy products and meat production and their supply to the appropriate regional and international markets can become a reality.

Nepal needs at least three well-equipped cold storage facilities, one in each major river basin. Such storage facilities are needed in regional market centres also. The establishment of such cold storage infrastructure facilities may require 600-800 MW of electricity if Nepal is seriously committed to the transformation of its subsistence agriculture to commercial agriculture. It is possible through the commercialization of high-value agriculture commodities that have distinct comparative advantages leveraging the regional markets in South Asia and China.

7.4 Market and supply-chain infrastructures

The market supply chain infrastructures provide agricultural commodities, including food, energy, medicine, and other products on which depends our way of life. Many different entities are responsible for the functioning of the market supply chain, including collection, transportation, and distribution from production centres, public-sector buyers, private-sector businesses, and other foreign and domestic partners. The supply-chain infrastructure system relies upon an interconnected web of transportation infrastructure and pathways, information technology, and energy networks connected to the local, regional, and international markets. While these interdependencies promote economic activities, they also serve to propagate risk across a wide geographic area or industry that arises from a local or regional disruption. Nepal's government, in collaboration with regional and private sector stakeholders, should undertake efforts to strengthen the supply chain mechanism.

Nepal should be able to capitalize on the regional and global supply chain system that supports and promotes trade in the region. Government should focus on the development of a national supply chain strategy that integrates a network of collection, transportation, and distribution infrastructures by which goods are moved from the point of production until they reach an end consumer. Such a strategy may include the promotion of efficient and secure movements of goods while protecting and securing the supply chain from exploitation and reducing its vulnerability to disruption. Another important aspect of such a strategy is to foster a national resilient supply chain system that is prepared for and can withstand evolving threats and hazards (as in the case of the Indian embargo in the past) and can recover rapidly from disruptions.

8. Conclusions

Despite abundant water resources, Nepal has not been able to utilize even 2 % of its water resource. It is the only resource whose appropriate development drives the development of infrastructures for all sectors. The sectoral development policy approach of water resource development needs to be replaced by a holistic, integrated approach of W-E-F-E nexus policy framework leveraging the synergistic interactions of the nexus elements. The W-E-F-E nexus policy framework offers the best opportunity for Nepal's development and prosperity. In view of the growing threat of climate change and its cascading impacts on Nepal's Himalayas, monsoon and seasonality driving the hydrological dynamics of Nepal's river systems, the adoption of the W-E-F-E nexus policy paradigm is not an option but a necessity for the integrated development of energy, irrigation, inland waterways, drought and flood mitigation, fisheries, and tourism infrastructures on which Nepal's development and prosperity invariably and decisively depends.

Multipurpose hydropower reservoir projects conceived from the WEFE nexus policy framework generate much-needed hydropower and provide much-needed irrigation and water supply infrastructures for food security and other consumptive uses critical for the integrated development of all sectors driving economic transformation and the prosperity of the country. If water resource development is driven exclusively with the singular objective of generating electricity and Nepal's rivers are handed over to the control of foreign companies like GMR and others, such an approach to water resource development would be suicidal to Nepal.

9. Policy recommendations

- Adopt and apply the W-E-F-E nexus policy framework to develop integrated and comprehensive water, energy, irrigation, inland waterways, flood mitigation, fisheries, and tourism cross-sectoral development analysis and navigation plans based on the baseline information in three major river basins.
- Identify potential upstream sites for the development of multipurpose hydropower reservoirs projects with the provisions of energy, irrigation, drinking water, inland waterways, and ecosystem services in each river basin and mark these project sites as the national high-priority projects that should not be compromised for the single purpose hydro-energy generation. Once such potential multipurpose water reservoir projects are compromised, the enormous multiple benefits that can be harvested will be forgone forever.
- Develop a well-equipped database of natural resources (water, lands, agriculture, forests, biodiversity, etc.) and river hydrology in each basin to assess cross-sectoral interactions, possible synergies and tradeoffs, and positive and negative externalities.
- Use the nexus approach to examine and identify potential synergies and tradeoffs across multiple sectors and scales to evolve harmonious policy and incentive structures across the water, energy, food, and ecosystem that can promote integration and synergy.
- Adopt a participatory approach to involve and engage all stakeholders (upstream

and downstream) within and across river basins to develop mechanisms for sharing costs and benefits and resolving conflicts and disputes.

- Engage policymakers, provincial and local government representatives, key stakeholders and the private sectors, civil society, and research institutions in the interactive sessions to better understand the challenges of water, energy, food, and ecosystem security within and across river basins and evolve policy instruments to ensure equitable sharing of the benefits and the costs.
- Establish cold storage and market-related infrastructures in each river basin for the collection and storage of agricultural produces (fruits, vegetables, food grains and animal products etc.).
- Establish fertilizer manufacturing plants in the appropriate location (perhaps the central region) of the country taking into consideration of supply-chain transportation network across the country.
- Develop inland waterways navigation, transportation, flood control, tourism, and regional and national market infrastructures.

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