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Optimization of economic return from water using water-energy-food nexus approach: A case of Karnafuli Basin, Bangladesh

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ABSTRACT

This study evaluates the existing situation of the water energy and food resource interaction using an indicator-based approach and optimizes the resource use in the Karnafuli River Basin. A water allocation model based on an optimization tool, LINDO 6.1, with an objective function to maximize the economic return, is developed to allocate water to different water use sectors (domestic, agriculture, energy, industry, and environment) in the basin. It is observed that 14.58 m^3 of water is required to generate 1 kWh of energy in Kaptai hydropower plant, while 4500 m^3 of water is consumed to produce 1 ton of crops in the basin. Due to improper management, around 12,500 ha of land under the Karnafuli Irrigation Project remains un-irrigated, which can be cultivated with high-yield Boro crop. Results show that by prioritizing the agriculture sector, a maximum economic return of US$ 30.3 million can be obtained; however, with this only 55% of the satisfaction level is achieved for the environment sector. Systematic and integrated management of the resources is required in Karnafuli Basin for socioeconomic and sustainable development.

1. Introduction

Water resources, energy, and food are the prime drivers of the economic development, political stability, and human sustainability of any country [7,17,20,37,44]. The issue of managing water resources is crucial for sustainable socioeconomic growth and human security over the coming decades [3,6,11,12,45,48]. The demand for water, energy, and food are increased due to the rapid expansion in population and extensive economic growth in cities [19,47], and water, energy, and food security have recently risen to global prominence as the demand is increasing. By 2050, the world population is estimated to rise by 34%, and water, energy, and food demand are expected to increase by 55%, 80%, and 60%, respectively [5,18,31,40]. As a consequence of fulfilling the demands, more supply of water is necessary that requires a substantial amount of energy in every major stage of freshwater supply- extraction, conveyance of water, treatment, and distribution [38]. However, energy production needs a significant amount of water at hydropower plants (key input), thermal power plants (to make steam and cooling purposes), and 90% of global electricity production depend on water [21,35]. The global energy cycle and food production are directly linked to the water resources systems [10,32,45]. An enormous amount of water is required to produce food in irrigation. Energy is needed to extract water from surface and underground sources for irrigation [16]. The residuals from agricultural sectors biomass also have the potential to produce bioenergy. Thus, in response to these drivers of increasing energy demand, population growth, economic development, urbanization, and climate change on water, energy, and food resources an adaptive management approach is urgent [14,27,42].

The relation between water, energy, and food is complex and dynamic, and they are the main driving force of socioeconomic advancement. The global water resource is finite and should be used effectively so that the other resources (i.e., energy and food) might not face any disturbances. One demand to be met will bring demand for the other two [21,29]. The capacity of these three resources is limited to meet the growing demand and is stressed due to the poor knowledge and the absence of an efficient management strategy [13,36].

Recent studies found that water, energy, and food are interlinked to produce one from the other and suggested considering them as Nexus [15,23]. [28] have applied a stakeholder-driven nexus approach to understanding the food-energy-environment nexus in the Lake Tana Subbasin of Ethiopia. The study compared and evaluated alternative development trajectories to these resources as the country aims to be middle-income by 2025. Similarly, Keskien et al. [30] describe that the nexus approach has significant potential to portray a richer picture of relation-

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ships and act as an emerging discourse for the sustainability of resources. The study by Do et al. [9] explores the trade-offs between three hydropower, irrigation, and fisheries sectors in the Lancang-Mekong transboundary basin by quantifying the effects of reservoir operation in these sectors through a hydro-economic optimization model. They conclude that these trade-offs can be turned into synergetic opportunities by enhanced reservoir operation, cross-sectoral and transboundary partnerships through stakeholder participation in decision making. Similarly, Duan et al. [10] carried out analysis of the water-climate-food security nexus in Turkmenistan, taking into account climate change, population growth, and three socioeconomic development scenarios. The study uses climate projections to analyze the water balance of the nation's main transboundary water source, the Amu Darya River Basin and evaluates future water use, crop yields, land and water productivities for the period 2016 to 2055. Results from the study assist authorities by providing a tool to identify vulnerabilities and manage the nexus of water, land, and energy resources to ensure future food security and sustainable socioeconomic development. Sharifi Moghadam et al. [43] suggested that the WEF nexus, in addition to ecosystem services, would guide to a better resource allocation efficiently without degrading the environment; and a better economic, higher sustainable development, and adaptation management at the basin scale. Similarly, Qin et al. [39] carried out a comprehensive evaluation of the WEFE system in Central Asia, considering the interdependencies between water, energy, food, and ecology, and the use of virtual water trade and food trade concepts to analyze the transmission of pressure between different sectors. Moreover, the study's development of cross-coordination mechanism for the sustainable development of WEFE systems emphasizes the need for an integrated governance and unified management across sectors and basins to ensure the smooth operation of WEFE security in Central Asia.

The present growth in the urban population and the possibility of future growth have alarmed the situation of water, energy, and food [47]. Thus, it is necessary to understand the nexus to resolve the resources issues simultaneously [42]. Although studies report different water, energy, and food nexus approaches, operationalization at a basin-scale is limited since the complexity of the nexus between resources increases with the increase in geographic scale. Apart from this, considerable data gaps, knowledge gaps, and a lack of appropriate tools to apply the nexus concept are major challenges for operationalizing the nexus approach [33].

A multipurpose water resource project in a basin can bring a dramatic change in the development of the national economy [2]. Kaptai multipurpose dam, one of Bangladesh's largest water resource projects, was constructed across the Karnafuli River to generate electricity, control floods, fulfill domestic and agricultural water demand, and for recreation and salinity control. During the monsoon season (June to September), when around 80 percent of the rainfall occurs, the dam's reservoir is insufficient to contain water. On the other hand, the amount of rainfall is lower in the other month. As a result, the amount of water available for the dry season is insufficient to meet downstream demand. Due to salinity intrusion in the dry season resulting from the inadequate water supply, the economic benefit from the thermal power plant, domestic water supply, and agriculture production is decreasing [24]. Thus, it is necessary to save water for the dry season.

Chittagong, the commercial capital of Bangladesh, is situated downstream of the Karnafuli river and is famous for its prime seaport. Despite having enough water, energy, and food resources in the basin, the city's development is falling behind due to the lack of a proper management system. Furthermore, demand for water, energy, and food sectors is anticipated to increase in the coming decades, driven by population growth, urban expansion, and economic growth. Therefore, a nexus approach has become a fundamental need for properly managing this river basin to deal with the demand. The nexus concept can aid the management bodies in gaining a better understanding of the current resource situations and maximize the benefits over the basin.

The objective of this study are therefore to systematically evaluate the existing situation and interlinkages between water, energy, and food sectors in the Karnafuli basin, and to optimize the water allocated to different water user sector to find the maximum economic return under different socioeconomic development scenarios in the basin. Very few previous studies have addressed these issues [22,26]. Specifically, our study adds insights into the: (1) system thinking and holistic assessment of water-energy-food nexus and interconnections of various factors affecting it; and (2) investigation of how future water requirements and water deficits impacts on the net economic return from different water user sector and optimize it under different socioeconomic development scenarios in the basin. Results obtained will assist concerning authorities in arriving at system-based interventions to tackle the water, energy and food security threats and effective water resources management in the Karnafuli River Basin.

2. Materials and methods

2.1. Study area

Situated in the eastern region of Bangladesh, the Karnafuli basin is located between 91°30′E – 92°45′E and 21°00′N – 23°30′N. Karnafuli river is the largest river in Chittagong, which originated in the Lushai hills in Mizoram, India, and runs 270 km in the southwest before meeting the Bay of Bengal [1]. The upstream portion of the river falls in hilly areas, and a downstream portion is fairly flat towards the southwest until it reaches the Bay of Bengal. It has a catchment area of 11,000 square kilometers and has two major tributaries named Halda and Ichamati River. In addition, there are many small streams that join with the Karnafuli River. Karnafuli River is referred to as a strong tidal river in Bangladesh. The velocity of the river water varies from 1.0 m/s to 1.5 m/s [25]. Karnafuli reservoir, situated in the Karnafuli basin, is elongated in the north-south direction and lies within narrow valleys between parallel ridges of hills. The location map and all the major power plants, industries, irrigation units, and water treatment plants in the Karnafuli basin are shown in Fig. 1.

The basin has a typical monsoon climatic zone and experiences a wide variation in rainfall, temperature, and humidity over the year. January is the coldest month, with the lowest monthly average temperature of 13 °C, while April and May are the hottest months, with the highest monthly average temperature of 32 °C. The medium hilly area of the Karnafuli river basin experiences about 2750 mm of rainfall annually, and 75% to 80% of the annual rainfall occurs in the monsoon period (June to September). On average, the maximum rainfall of about 600 mm occurs in July with twenty-six rainy days and about 5 mm in January with only two rainy days.

The soil of the Karnafuli Irrigation Project (KIP) area is identified as primarily a recent alluvium mineral in character as developed by the natural drainage system. The remaining soil type in the project area is a brown hill and gray piedmont. Soil textures are mostly loamy, followed by clayey. The soils are deep and leveled, well suited to cultivate rice in the irrigation project area.

There are two surface water treatment plants alongside the Karnafuli River operated by the Chittagong Water Supply and Sewerage Authority (CWASA). Mohra Water Treatment Plant has a monthly production capacity of 90 MLD or 2.70 MCM. The construction of this plant was implemented between the years 1988 and 1990. Karnafuli Water Treatment Plant is part of the "Karnafuli Water Supply Project" – a three-package scheme undertaken in 2006 to ease the water crisis and improve the distribution system in Chittagong. Construction of the plant on the Karnafuli riverbank in the Pomona area of Rangunia was completed in October 2016. The plant has a production capacity of 143 MLD or 4.2 MCM per month, increasing the water supply to the city by 30%. And another phase of 4.2 MCM per month water production capacity is being constructed.

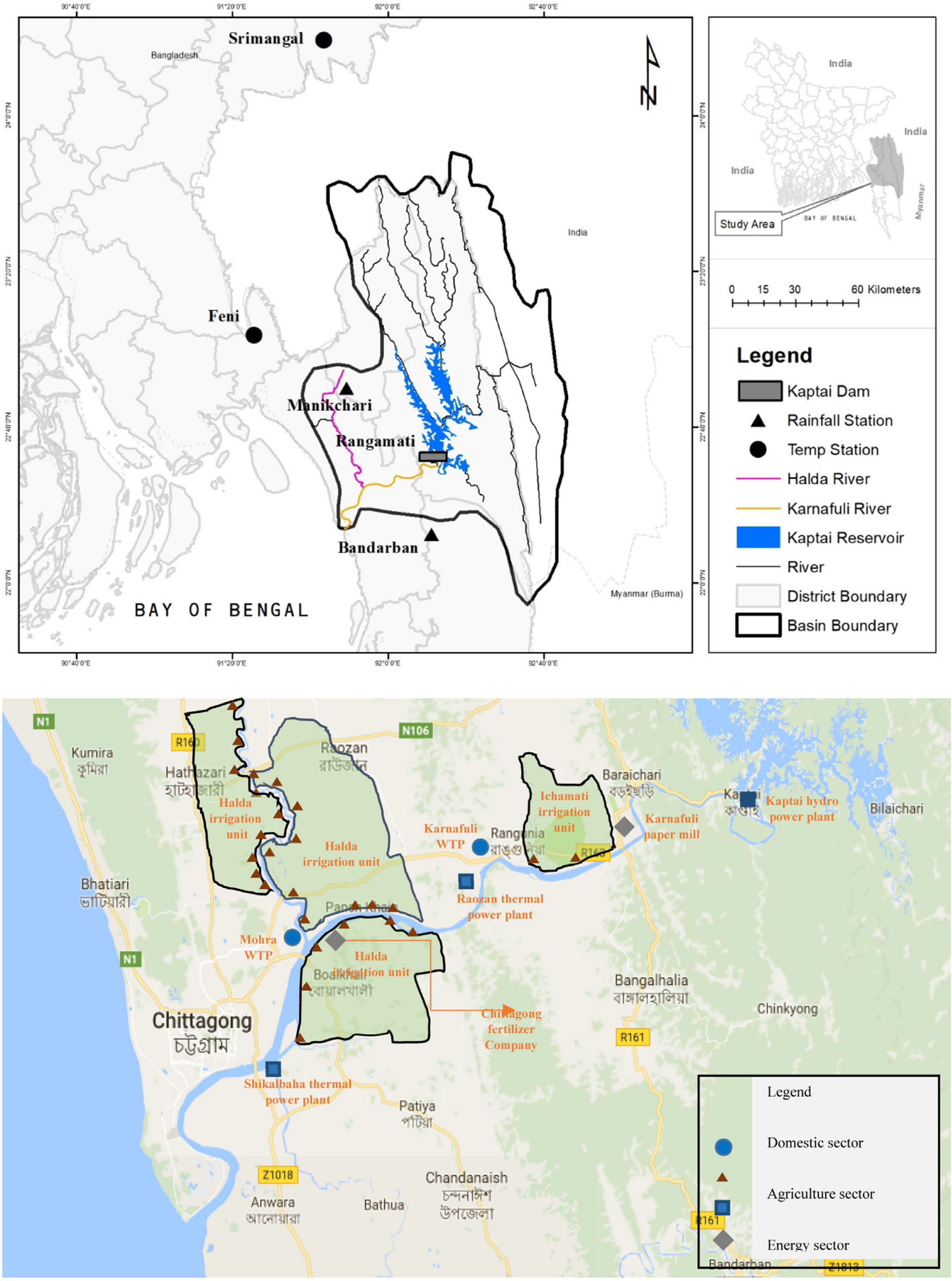

Fig. 1. Location map and water intake point of different users at the Karnafuli River Basin.

The Karnafuli irrigation project, one of the major irrigation projects of the country, provides irrigation, flood control, and drainage in the study area. It consists of two units: the Ichamati unit and the Halda unit. The total arable area of these two units is 3,237 hectares and 15,378 hectares, respectively. In the Halda Unit, the channel system is supplied by tidal recharge, whereas in the Ichamati Unit, it is supplied by the main pumping plant. In both areas, diesel-powered low lift pumps raise water from the channels to adjacent farmlands. The agricultural area within the Karnafuli River Basin primarily focuses on rice cultivation, with three distinct categories of seasonal rice production present in the study area: *Aus*, *Aman*, and *Boro* rice. During the dry season, spanning from November to February, the primary crops grown in the study area are *Boro* rice, pulses and vegetables. Conversely, during the monsoon season, from March to June, the cultivation of predominantly *Aus* rice takes place, while *Aman* rice is grown from July to October in the study area.

Table 1
Summary of data.

Sector	Data types	Duration	Frequency	Unit	Sources
Domestic	Raw water extraction from the Karnafuli river by Mohra WTP	2007–2016	Monthly	MCM/month	Chittagong Water Supply and Sewerage Authority (CWASA); Bangladesh Power Development Board (BPDB)
	Raw water extraction from the Karnafuli river by Karnafuli WTP	2007–2016	Monthly	MCM/month	
	Electricity consumption by Mohra WTP to supply water to the consumers	2007–2016	Monthly	GWh/month	
	Electricity consumption by Karnafuli WTP to supply water to the consumers	2007–2016	Monthly	GWh/month	
	Total sell and cost of production by two WTP	2016	Monthly	US$	
Agriculture	The amount of water supply to the Ichamati and Halda Irrigation units	2007–2016	Monthly	MCM/month	Bangladesh Water Development Board (BWDB); Bangladesh Agricultural Development Corporation (BADC)
	Monthly total amount of electricity and diesel fuel consumption to supply water	2007–2016	Monthly	GWh/month	
	Total seasonal raw crop production from Ichamati and Halda Irrigation units	2007–2016	Seasonally	Ton	
	Total sell and production cost for various crops	2016	Seasonally	US$	
Hydropower	Total amount of water released from the reservoir	2007–2016	Monthly	MCM/month	Bangladesh Power Development Board (BPDB)
	Electricity generation from the Kaptai hydropower plant	2007–2016	Monthly	GWh/month	
	Production cost and benefits	2016	Monthly	US$/kWh	
Energy	Amount of raw water withdrawn from the Karnafuli river	2007–2016	Monthly	m^3/day	Raozan power plant, BPDB
	The amount of electricity generation per day	2007–2016	Monthly	GWh/day	
	Production cost and benefits	2016	Monthly	US$/kWh	
	Amount of raw water withdrawn from the Karnafuli river	2007–2016	Monthly	m^3/day	Shikalbaha thermal power plant, BPDB
	The amount of electricity generation per day	2007–2016	Monthly	GWh/day	
	Production cost and benefits	2016	Monthly	US$/kWh	
Industrial	Amount of raw water extracted from Karnafuli river	2007–2016	Monthly	m^3/day	Karnafuli Paper Mills Authority
	Monthly paper Production	2007–2016	Monthly	Metric ton per month	
	Total amount of electricity consumed	2007–2016	Monthly	GWh/ month	
	Total production costs and total benefit	2016	Monthly	US$	

Kaptai Hydropower Plant is the only hydropower plant in the country located in Kaptai, about 50 km from the port city of Chittagong. This plant was constructed in 1962 as part of the 'Karnafuli Multipurpose Project' and is one of Bangladesh's biggest water resources development projects. After being commissioned in 1962, the plant could feed the national grid with 80 MW of electricity. In 1988, the generation capacity was increased in two phases to a total of 230 MW. The reservoir water storage capacity is 6,477 MCM.

Raozan thermal and Shikalbaha thermal power plants are the two gas-fired thermal power in the Karnafuli river basin. The monthly maximum water withdrawal from the Karnafuli River is 1200 m^3/hour and 171.43m^3/hour, respectively, for cooling purposes. And they generate a maximum of 200 GWh and 35.4 GWh of electricity per month, respectively.

In 1990–91, the installed capacity of Karnafuli Paper Mill (KPM) raised to 33,000 metric tons, and the budgeted production was 28,438 metric tons, while the actual production was 30,216 metric tons per year. In 2009–10, the amount of production of KPM was 24,201 metric tons per year. Karnafuli paper mill can withdraw a maximum of 3.44 MCM per month while its actual withdrawal is 2.0 MCM.

2.2. Data

Different types of data from many governmental and non-governmental authorities were collected for the analysis. Table 1 shows data collected from the various organizations in different frequencies with its sources mostly from 2007 to 2016.

2.3. Methodology

2.3.1. Conceptual framework

This study evaluates different water energy food resources indicators in the Karnafuli River Basin, followed by the net economic return from different water user sectors. Based on the demand of every sector, the sectoral supply of water is optimized through an optimization technique so that the net economic return from the basin can be maximized.

The interlinkage among the three resources in different sectors is quantified in the study through an indicator-based approach, as shown in Fig. 2. In addition, the total sectoral demand for water is evaluated, and based on the total available water (AW) in the basin; different water supply scenarios were developed. Each scenario was analyzed in an optimization tool LINDO (Linear, Interactive, and Discrete Optimizer) version 6.1 to find the optimal water supply scenario so that maximum benefit from the water user sector is attained. LINDO is a useful tool for solving linear, nonlinear, integer, stochastic, and many other programming problems that are well-known in the business, research, industry, and personnel, i.e., product scheduling and distribution, inventory management, resource allocation, profit maximization cost minimization and more. The optimization procedure of the sectoral water supply scenario to find the maximum benefit from the water supply is illustrated in Fig. 2.

2.3.2. Calculation of WEF nexus indicators

2.3.2.1. Water requirement to energy production. Current energy production in the basin area relies mainly on hydropower and gas-feed thermal energy. Water consumption is mainly caused by evaporation losses from the reservoir. The total water required for hydropower generation is the amount of water that passes through the turbines and spillway. Likewise, the total water required for thermal power is the water consumed in cooling process and evaporation through steam. Total electricity generated per unit volume of water in hydropower and thermal power is estimated using the Eq. (1) and (2). Eq. (3) gives the overall energy generated with unit volume water in the basin.

$$\text{Per unit hydropower production, } E_H = \text{total electricity generated/total water required for hydropower } (W_h) kWh/m^3 \tag{1}$$

$$\text{Per unit thermal power production, } E_T = total\ electricity\ generated / total\ water\ required\ for\ thermal\ power\ plant\ (W_t) kWh/m^3 \tag{2}$$

$$Energy\ production\ in\ exchange\ of\ water = \left(E_H * W_h + E_T * W_t\right)/(W_h + W_t) kWh/m^3 \tag{3}$$

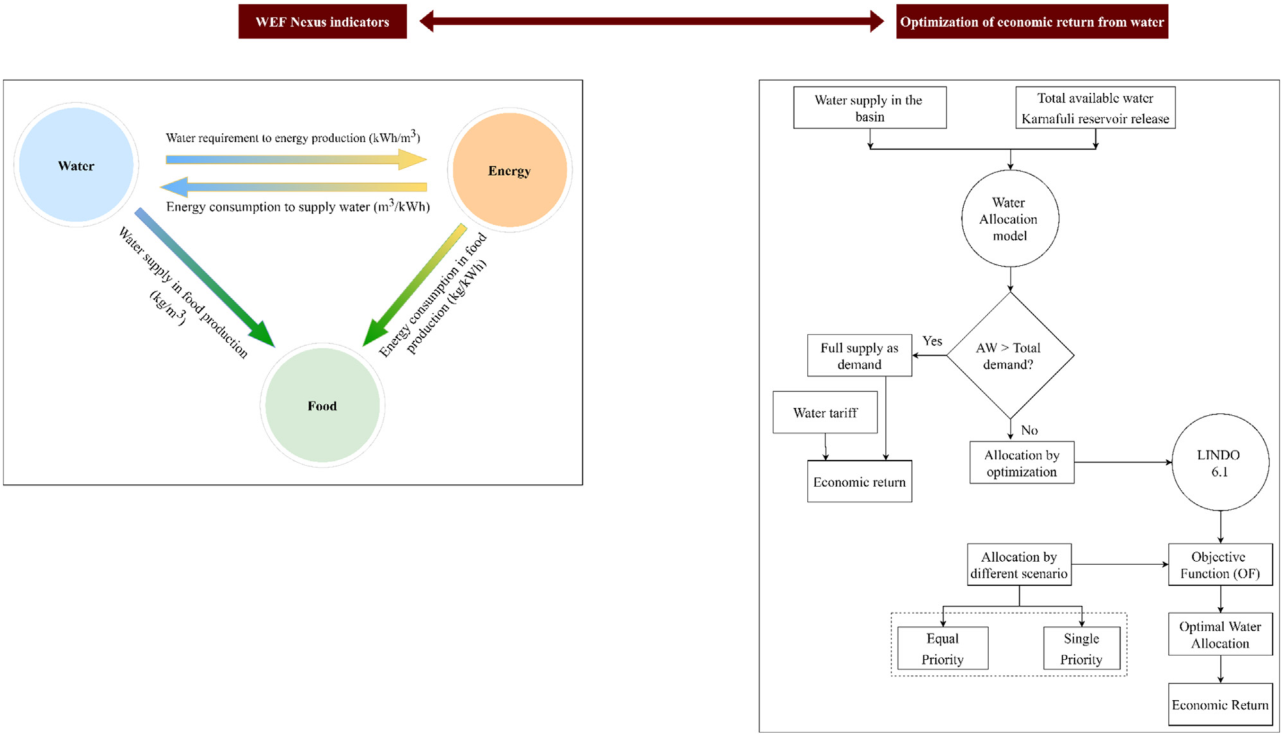

Fig. 2. Framework for optimization of the economic return using water-energy-food nexus approach in Karnafuli Basin.

2.3.2.2. Water supply in food production. Food production describes only the raw production of crops in the basin. Water consumption of agriculture in the basin is calculated as the sum of the total water footprint of the crop production and the losses through evaporation. The return flow from the crop field is not considered water consumption as it is returned to the basin system. The total water supplied is the amount of surface water supplied from sowing to harvesting period for the irrigated crops. Eq. (4) provides an estimation of the amount of food produced per unit volume of water use in the basin.

$$\text{Food production per unit of water, } F = \textit{total food production/total water supplied}\ kg/m^3 \tag{4}$$

2.3.2.3. Energy consumption to supply water. A considerable amount of energy is required in water services: abstraction, transport, treatment, and distribution. Water utility services of Chittagong city also operate some deep tube well to fulfill the water demand partially. The total surface water production is the amount of water produced after treatment. Likewise, the total energy required is the amount of energy required for abstraction, transportation, treatment and distribution process in surface water services while it is the amount of energy required for pumping in groundwater. Eq. (5) and (6) estimates the volume of surface water and ground water produced per unit of energy consumed for production. Eq. (7) gives the overall water produced with unit energy consumed in the basin.

$$\text{Surface water supply, } W_S = total\ surface\ water\ production/total\ energy\ consumed\ \left(E_S\right)m^3/kWh \tag{5}$$

$$\text{Groundwater supply, } W_G = total\ groundwater\ production/total\ energy\ consumed\ \left(E_G\right)m^3/kWh \tag{6}$$

$$\text{Water supply per unit of energy consumption} = \left(E_S * W_S + E_G * W_G\right)/(E_S + E_G)m^3/kWh \tag{7}$$

2.3.2.4. Energy consumption in food production. The food production sector's energy consumption comprises the energy consumed for agricultural production only without considering the energy consumed in food processing. Electricity is consumed to supply water through pumping for irrigation purpose. Likewise, the basin has low lift fuel pump, where diesel is used as fuel, to lift water from the channel to the crop field. Eq. (8) and (9) estimates the total food produced in the basin per unit electricity and fuel consumed from sowing to harvesting period in the basin.

$$\text{Food production with unit electricity } F_E = total\ food\ production/total\ electricity\ consumed\ \text{kg/kWh} \tag{8}$$

$$\text{Food production with unit fuel, } F_S = total\ food\ production/total\ fuel\ consumed\ \text{kg/liter of diesel} \tag{9}$$

2.3.3. Calculation of net economic return (NER)

This study has attempted to determine the price of one cubic meter of water for various sectors in the Karnafuli river basin. The net economic return from four different water user sectors is formulated in the following section.

2.3.3.1. NER from the domestic sector. CWASA follows a tariff rate for selling water to consumers. In this study, the total cost to supply water includes only the chemical cost, operation, and maintenance cost, and electricity cost. Thus the net economic return from the domestic sector is calculated using Eq. (10).

$$NER_{CWASA} = \left(P_{wp} - C_{wc}\right)/WW_m \tag{10}$$

$$P_{wp} = W_p * P_{avg} \tag{11}$$

$$C_{wc} = C_{prod} + WW_m * W_{sc} \tag{12}$$

Where,

NER_{CWASA} = net economic return from CWASA (US\$/m^3); P_{wp}= total return from water supply (US\$); W_p = total water production (m^3); P_{avg}= Average unit selling price (US\$/m^3); C_{wc}= total selling cost (US\$); C_{prod} = total production cost (US\$); WW_m= water withdrawn (m^3); W_{sc}= water supply cost (US\$/m^3)

2.3.3.2. NER from the energy sector. The net economic return from hydropower is calculated by multiplying the power production by the difference between the power selling price and the power-producing cost over the water passing through the power plants. This results in the net benefit per unit amount of water derived by Babel et al. [4] and Divakar et al. [8], shown in Eq. (13).

$$NER_{HPP} = \left(P_{prod} * \left(P_{price} - P_{cost}\right)\right)/W_p \tag{13}$$

Where,

NER_{HPP} = net economic return from Hydropower plant (US\$/m^3); P_{prod} = Total power production (kWh); P_{price} = Average selling price (US\$/kWh); P_{cost} = average production cost (US\$/kWh); W_p= Water passing through the plant (m^3)

In the thermal power plant, water is required for cooling purposes. The net economic return from Raozan thermal power plant (RPP) and Shikalbaha thermal power plant (SPP) is calculated using Eq. (14).

$$NER_{RPP,SPP} = \left(P_{prod} * \left(P_{price} - P_{cost}\right)\right)/W_s \tag{14}$$

Where,

$NER_{RPP,\ SPP}$ = net economic return from RPP or SPP (US\$/m^3); P_{prod} = total power production (kWh); P_{price} = Average selling price (US\$/kWh); P_{cost} = Average production cost (US\$/kWh); W_s = Water supply to the plant (m^3)

2.3.3.3. NER from the agricultural sector. The residual imputation method is widely used to calculate the net benefit from different crops per year, as proposed by [41]. This method is used in a few earlier works, such as Babel et al. [4] and Divakar et al. [8], presented in Eq. (15).

2.3.3.5. NER from the environment sector. In this study, the minimum flow for salinity control has been considered an environmental requirement that affects the different sectors of the basin. The NER from the environment sector can be measured by Eq. (19):

$$NER_{environment} = \left(C_{extra} * WW_A\right)/W_e \tag{19}$$

Where,

C_{extra}= Extra cost due to salinity; WW_A= Total water flow in the agriculture sector; W_e = Total flow in salinity control (environment) sector

2.3.4. Economic analysis of water allocation scenarios

Different allocation cases are developed based on the normal demand, anticipated maximum demand, and availability of water. The monthly normal water supply and demand by various sectors is presented in Table 2.

Likewise, the monthly maximum water demand of Karnafuli river by sectors is presented in Table 3.

By considering priority to be single and multiple sectors, the model is assessed to evaluate the net economic benefit of the Karnafuli river basin. These developed scenarios as tabulated in Table 4, offer a wide illustration of the condition to the policymakers and permit them to take the best scenario, which improves the water management of this water-scarce river.

2.3.5. Optimization of economic return

The amount of water supplied to various sectors is the model's variable. The optimization function or objective function of the model in this study is defined by the summation of the products of allocated water and the net economic return of the sectors, as shown in Eq. (20).

$$OF = \sum_{i=1}^{n} S_i * NER_i \tag{20}$$

Where,

$$NER_{agri} = \sum_{1}^{n} \left[\left\{ \frac{(A * Y * P)agr, cp - A * (F + M + L + O)agr, cp - WS_{agr} * \sum_1^m MW(agr, m)}{\sum_1^m MW(agr, m)} \right\} \right] * \left\{ \frac{\sum_1^m MW(m, cp)}{\sum_1^n MW(m, cp)} \right\} \tag{15}$$

Where,

$\mathrm{NER_{agri}}$ = Net economic return from agriculture (US\$/m^3); agr = Agriculture; cp = Crop; m = Month; n = no of crop; A = Area under a crop (ha); Y = Actual yield of a specific crop (t/ha); F = Fertilizer cost (US\$/ha); M = Machinery cost (US\$/ha); L = Labor cost (US\$/ha); O = other production cost (US\$/ha); P = Crop price (US\$/t); WSagr = Water supply cost (US\$/m3); MW(agr,m) = Monthly withdrawal for irrigation (m^3)

2.3.3.4. NER from the industry sector. The monthly net economic return from Karnafuli Paper Mill (KPM) is calculated using Eq. (16).

$$NER_{KPM} = \left(P_{total} - C_{total}\right)/WW \tag{16}$$

$$P_{total} = n * P_s \tag{17}$$

$$C_{total} = n * C_c + WW * W_{wc} \tag{18}$$

Where,

NER_{KPM}= net economic return from KPM (US\$/m^3); P_{total}= Monthly total return from KPM (US\$); n= monthly total unit production (mt); P_s= Average unit selling price (US\$/mt); C_c= monthly unit production cost (US\$/mt); C_{total}= total production cost (US\$); WW = Monthly water withdrawn from the river (m^3); W_{wc}= monthly water withdrawal cost (US\$/m^3)

OF= objective function to maximize the economic return; S_i= water supplied to the sector i (m^3); NER_i= net economic return per unit volume of water from sector i (US\$/m^3)

2.3.5.1. Constraints of the model. The optimization allocation model by linear programming maintains three kinds of constraints, physical (mass balance) constraints, policy (upper bound and lower bound of variables) constraints, and feasibility (non-negativity) constraints. Thus, the constraints of the model are given below.

(i) Availability of water

$$\sum_{i=1}^{n} S_i \le AW \tag{21}$$

(ii) Water demand and supply constraints

$$D_i \ge S_i \tag{22}$$

For assumed maximum demand,

$$D_{max\ i} \ge S_i \tag{23}$$

(i) Non-negativity constraints

$$D_i \ge 0 \tag{24}$$

$$S_i \ge 0 \tag{25}$$

$$D_{\max i} \ge 0 \tag{26}$$

Table 2
Monthly normal water supply and normal demand of Karnafuli River by sectors (10^6 m^3).

Month	Sector						Normal Demand
	Domestic	Agriculture	Energy	Industry	Environment	Total	
Jan	2.75	48.20	1.02	2.20	724.56	778.73	803.52
Feb	2.57	54.24	0.92	2.09	655.21	715.03	725.76
Mar	2.82	87.23	1.02	2.35	643.47	736.89	803.52
Apr	2.77	74.62	0.99	2.31	644.64	725.82	777.60
May	2.85	34.63	1.02	2.29	962.69	1003.47	803.52
Jun	2.83	39.84	0.99	2.25	1561.18	1607.09	777.60
Jul	2.83	35.66	1.02	2.20	2694.39	2736.11	803.52
Aug	2.82	32.73	1.02	2.31	2418.66	2457.54	803.52
Sep	2.76	31.17	0.99	2.07	1725.27	1762.25	777.60
Oct	2.78	33.06	1.02	2.17	1363.60	1402.62	803.52
Nov	2.75	5.64	0.99	2.28	898.79	910.45	777.60
Dec	3.10	41.37	1.02	2.15	735.64	783.28	803.52

Table 3
Monthly maximum water demand of Karnafuli River by sectors (10^6 m^3).

Month	Sector					Total
	Domestic	Agriculture	Energy	Industry	Environment	
Jan	7.223	73.44	1.02	2.2	749.35	833.233
Feb	6.524	76.2	0.92	2.09	665.94	751.674
Mar	7.223	125.59	1.02	2.35	710.1	846.283
Apr	6.99	118.4	0.99	2.31	696.92	825.610
May	7.223	60.3	1.02	2.29	762.74	833.573
Jun	6.99	50.73	0.99	2.25	731.69	792.650
Jul	7.223	57.77	1.02	2.2	761.8	830.013
Aug	7.223	45.07	1.02	2.31	764.64	820.263
Sep	6.99	50.33	0.99	2.07	740.62	801.000
Oct	7.223	41.08	1.02	2.17	764.5	815.993
Nov	6.99	11.91	0.99	2.28	765.94	788.110
Dec	7.223	71.39	1.02	2.15	755.88	837.663

Table 4
Scenarios analyzed in this study.

Scenario	Description
Scenario 0	Existing demand condition
Scenario 1	Demand of all sectors is increased by 20%
Scenario 2	Demand of all sectors is increased by 50%
Scenario 3	3.1 existing demand condition
Agriculture sector is	3.2 demand of all sectors is increased by 20%
given first priority	3.3 demand of all sectors is increased by 50%
Scenario 4	4.1 existing demand condition
Environment sector is	4.2 demand of all sectors is increased by 20%
given first priority	4.3 demand of all sectors is increased by 50%
Scenario 5	5.1 existing demand condition
Reservoir release is	5.2 demand of all sectors is increased by 20%
reduced by 20%	5.3 demand of all sectors is increased by 50%

Where,

AW = Availability of water; D_i = Normal water demand by sector I; S_i = water supply to the sector I; $D_{max\ i}$ = Proposed maximum water demand by sector i

3. Results and discussion

3.1. Water and energy in different sectors

The status of supply and consumption of both water and energy resources in different sectors within the study area has been analyzed in this section.

3.1.1. Domestic sector

The present population of Chittagong City is about 4.42 million (projected from Census data, 2011), and almost 92% is under Chittagong City Corporation (CCC). Out of that, 2.4 million of the population are served with piped water connection which is about 60% of the total population under the CCC area of responsibility. Though the service coverage of CCC is increasing, it is not enough to fulfill the higher increasing rate of population. The total amount of water production per year has remained almost the same from 2007 to 2016. Due to the start of a new surface water treatment facility, total water production in 2016 was about 71 million cubic meters, the highest on record. The hilly Chittagong city water supply authority depends on surface water sources as well as groundwater sources. In 2007, the authority extracted groundwater at a rate of almost 36 million cubic meters, which was 52.35% of total water production. But in 2016, surface water production was higher (more than 37 million cubic meters), which comprises about 52.19%, as illustrated in Fig. 3(a). The energy consumption for both surface water and groundwater includes the electricity for pumping raw water from the sources, treatment, and distribution. For groundwater supply, an average 20GWh of electricity is consumed per year, whereas for surface water, the margin is 12.5GWh. The energy consumption for both water sources from 2007 to 2016 is shown in Fig. 3(b).

3.1.2. Agricultural sector

Ichamati unit has 3,237 hectares of irrigable land. Three types of paddy (*Aus, Aman,* and *Boro*) are being produced, which comprised about 28%, 88%, and 66% of total available land. Various types of vegetables are also produced in around 590 hectares (only 18%). The average yield of *Aus, Aman,* and *Boro* rice is 2.88 tons/ha, 3.94 tons/ha, and 4.19 tons/ha, respectively. Water is supplied from the Karnafuli River to the Ichamati unit mainly through pumping from December to June, while rainwater is the source of irrigation for the rest of the month. Rain-fed *Aman* rice is cultivated in the monsoon season (Mid July to October), where irrigation by pumping and electricity consumption is negligible. The highest amount of water supplied in the Ichamati unit

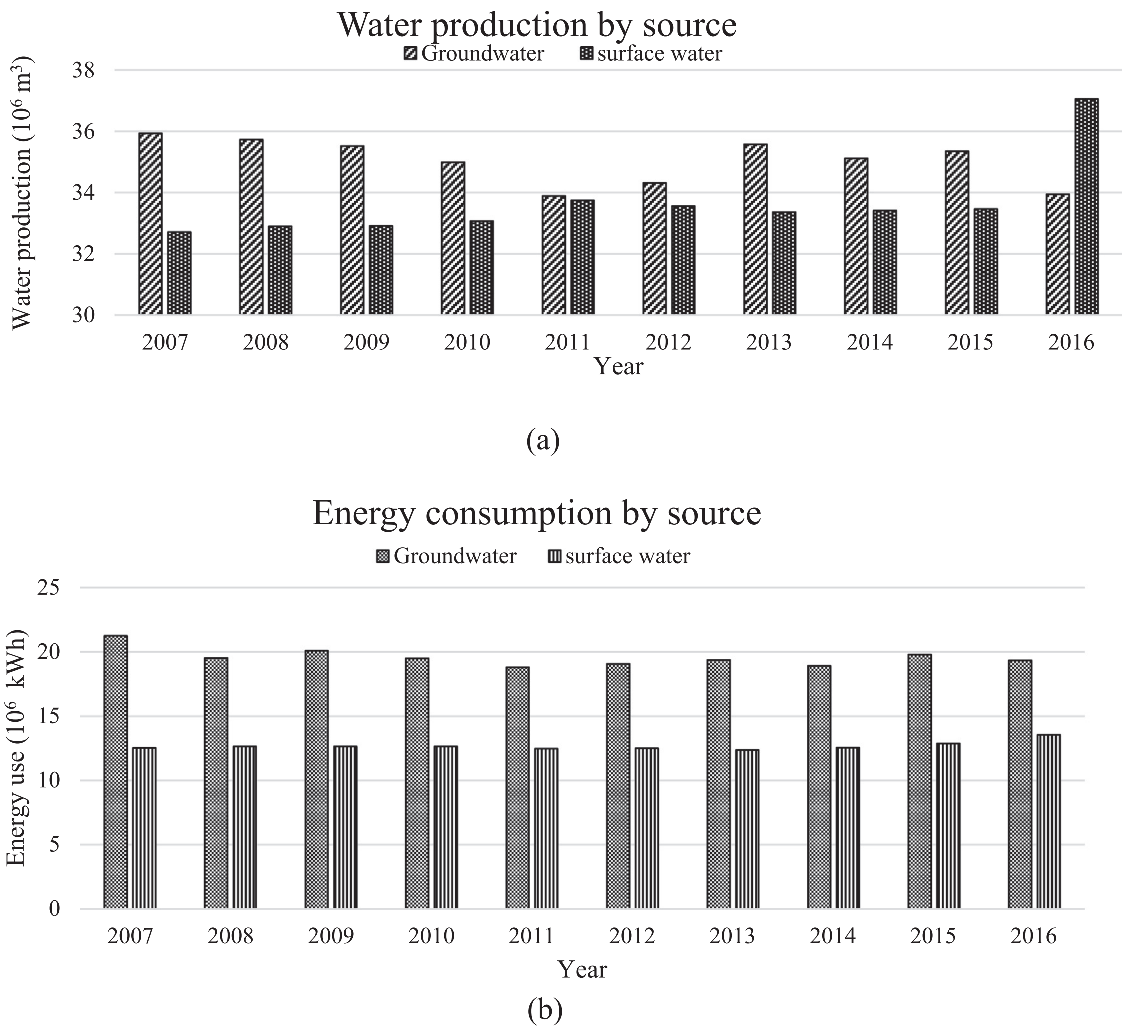

Fig. 3. (a) Annual water supply and (b) Annual energy consumption by surface and groundwater source in CWASA.

was 116 MCM, and electricity consumption was 415 MWh in 2009, resulting in the highest yields, as illustrated in Figs. 4(a) and (b).

Halda unit covers about 15,378 hectares of agricultural land. The three types of paddy (*Aus, Aman*, and *Boro*) produced in this unit comprise about 9%, 54%, and 27% of total available land with an average yield of 2.81 tons/ha, 3.74 tons/ha, and 3.94 tons/ha respectively. Various types of vegetables in three seasons and pulses are also produced in around 1,790 hectares and 537 hectares which are only 8% and 2.4%, respectively. In this unit, water is mainly supplied through the canal from the Halda River, with no electrical pumping required from December to June. A small amount of surface water is supplied from June to October for the rain-fed crop *Aman* rice. The high-yielding crop *Boro* consumes about 46% of total water supplied (430 MCM/year) in comparison to *Aman,* which consumes about 37%, and *Aus* with 15% of total water supplied, as shown in Fig. 5(a). The amount of water consumed by pulses and vegetable are negligible compared to total water consumption. In the dry season, an average of 98 liters of diesel oil is consumed per hectare for the *Boro* crop. Likewise, an average of 28.5 liters of diesel per hectare is consumed for *Aman* and 80 liters per hectare of land for the *Aus* crop, as shown in Fig. 5(b).

3.1.3. Energy sector

The Karnafuli river basin consists of three power generation sources: Kaptai hydropower, Raozan, and Shikalbaha thermal power plants which contribute 44.11%, 52.14%, and 3.75% respectively of the total electricity generation. The Shikalbaha thermal power plant produces less than its total generation capacity. Throughout the year, 73% of total power generates from April to October, as shown in Fig. 6, which is 25% more than the whole year average because of water availability. In the Raozan thermal power plant, the month-wise maximum electricity of 230 GWh is generated in April, while it is 24 GWh for the Shikalbaha thermal power plant. The variation in these two thermal plants is because of the inadequate fuel supply to the Shikalbaha thermal power plant, thus, resulting in six months shutdown of the power plant almost every year.

In the Kaptai Hydropower plant, the power generation is less from December to May due to inadequate water flow, thus increasing the water requirement. In May, the maximum water intensity is about 21.79 m^3/kWh, whereas the monthly average is 14.58 m^3/kWh, as shown in Fig. 7(a). However, the water flow is higher from July to November, and surplus water is passed through the spillway. Likewise, energy intensity in Raozan and Shikalbaha thermal power plants is given in Fig. 7(b). The Raozan power plant has higher energy generation per unit water supplied than the Shikalbaha power plant, thus has higher energy intensity than the Shikalbaha power plant. About 1200 m^3 of water per hour and 172 m^3 of water per hour is withdrawn from the Karnafuli river for cooling purpose in Raozan and Shukalbaha thermal power plant respectively.

In contrast to the Kaptai Hydropower plant, the electricity generation rate in these two thermal power plants is higher from April to August. Raozan power plant generates maximum electricity of about 150 kWh/m^3 in April, while Shikalbaha power plant generates maxi-

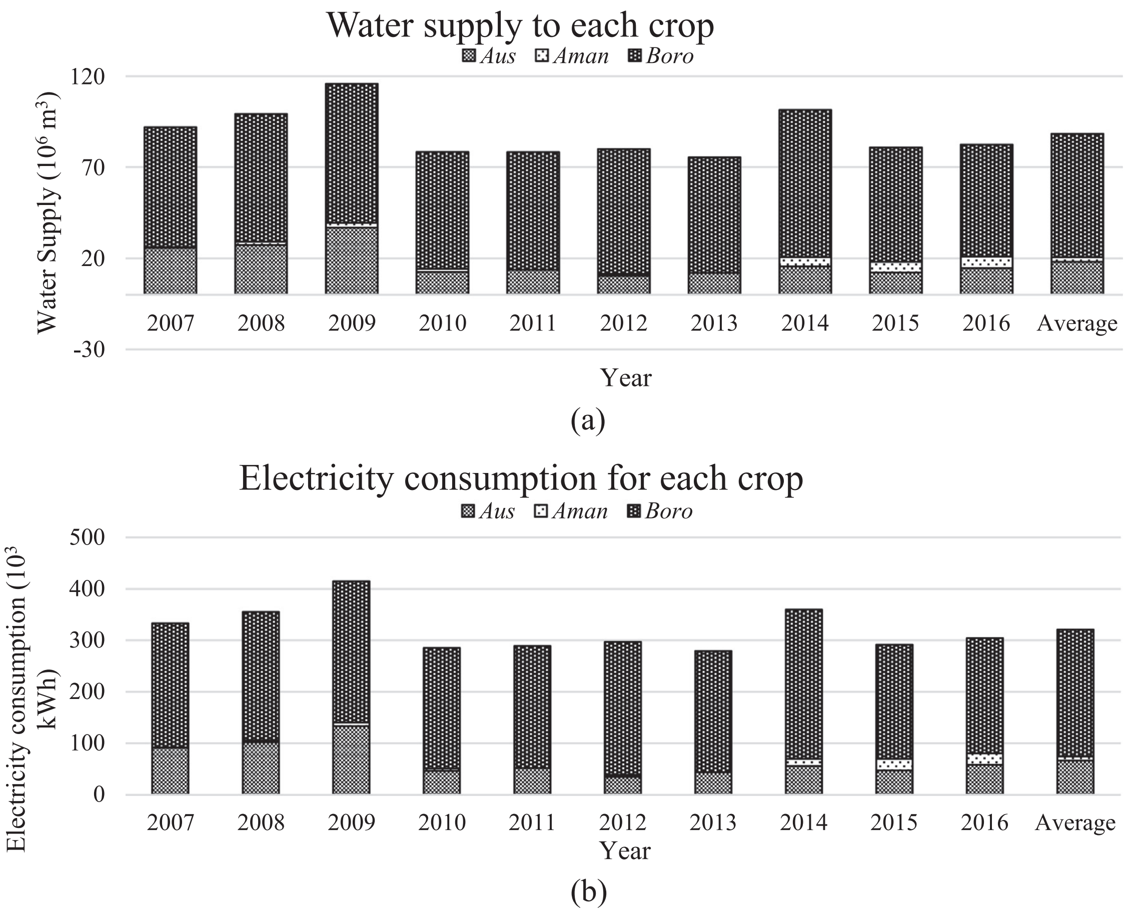

Fig. 4. (a) Water supply, (b) Electricity consumption for different types of crops in Ichamati Unit.

mum electricity of about 70 kWh/m^3 in June. Considering both power plants, an average of 81 kWh of thermal electricity can be produced by 1 m^3 of water.

3.1.4. *Industrial sector*

The largest paper mill in Bangladesh, the Karnafuli paper mill, lies in this river basin. Karnafuli paper mill's production decreases year to year because of a lack of raw materials like wood and bamboo. The mill's production reduced to 9,000 metric tons from 25,000 metric tons over the past decade, as shown in Fig. 8 below. The production rate of the Karnafuli paper mill is inversely related to water and electricity consumption. It can be observed that the paper production was highest in 2009, and it required 2.83 MWh of electricity and 1,110 m^3 of water per metric ton of paper production. However, in 2016, an additional increase of 50% electricity and 95% water was required to produce one metric ton of paper.

3.2. *WEF nexus indicators*

In this section, the interlinkage among the water, energy, and food sectors has been quantified using the set of indicators mentioned in Section 2.3.2. The overall water, energy, and food resources interaction in the Karnafuli basin from 2007 to 2016 is presented in Fig. 9.

3.2.1. *Water in energy production*

In the Kaptai hydropower plant, a total of 112.29 BCM (billion cubic meter) of water was required to generate 7,700 GWh of electricity from 2007 to 2016. Likewise, a total of 120 MCM of water was withdrawn from the Karnafuli river for cooling purposes in the Raozan and Shikalbaha thermal power plant and a total of 9,760 GWh of electricity was generated from the two plants from 2007 to 2016. Based on the Eq. (1), (2), and (3) in Section 2.3.2, it was observed that hydropower production consumes about 14.58 m^3 of water to produce unit kWh of energy. In contrast, thermal power production consumes about 0.012 m^3 of water to produce unit kWh of energy and the overall water consumed for unit energy production in the Karnafuli basin is 6.44 m^3/kWh. The Kaptai hydropower plant is water intensive in comparison to the thermal power plants to generate electricity.

3.2.2. *Water in food production*

A total of 5,184 MCM of water was used in the Ichamati and Halda irrigation units to produce 1,150 kton of crop from 2007 to 2016. Using Eq. (4) of Section 2.3.2, it was estimated that, about 0.22 kg (less than 1 kg) of crops was produced with 1 m^3 of water in the basin. The water consumed of 4500 m^3/ton of rice production in the basin is three times higher than the global average of 1,486 m^3/ton for rice production, as suggested by [34].

3.2.3. *Energy to supply water*

Based on Eqs. (5), 6, (7) in Section 2.3.2, it is observed that 0.38 kWh of energy is required to produce a unit volume of surface water. Likewise, 0.56 kWh of energy is required for the unit volume of groundwater pumping. The basin consumes more energy for the production of groundwater than surface water. The overall energy consumed for water production in the basin is 0.47 kWh/m^3. As reviewed by [46], the global average energy intensity for surface water production is 0.37 kWh/m^3, while it is 0.48 kWh/m^3 for groundwater production. The energy intensity for groundwater production in the Karnafuli basin is slightly higher than the global average.

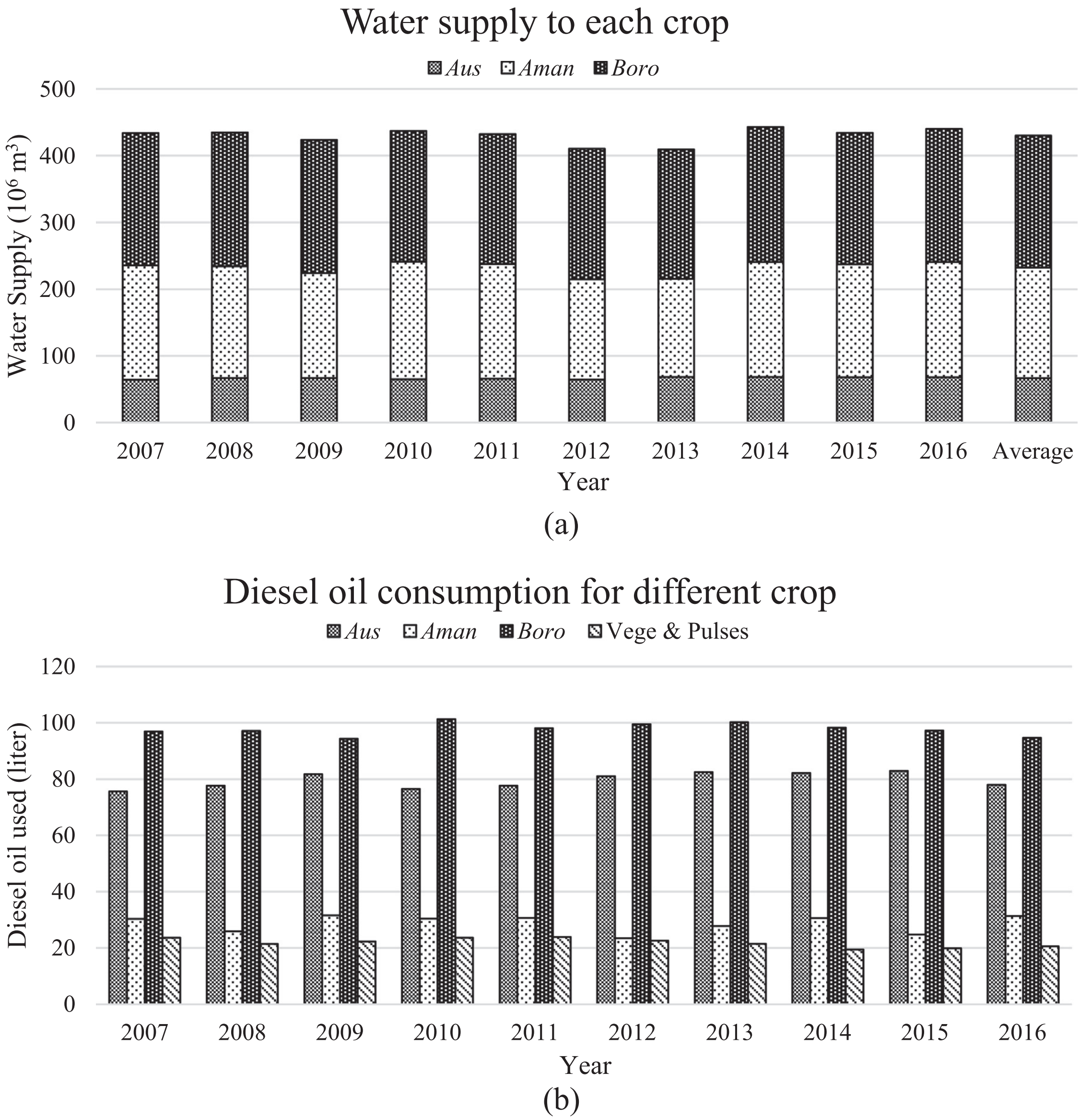

Fig. 5. (a) Water supply, (b) Diesel oil consumption for different types of the crops in Halda Unit.

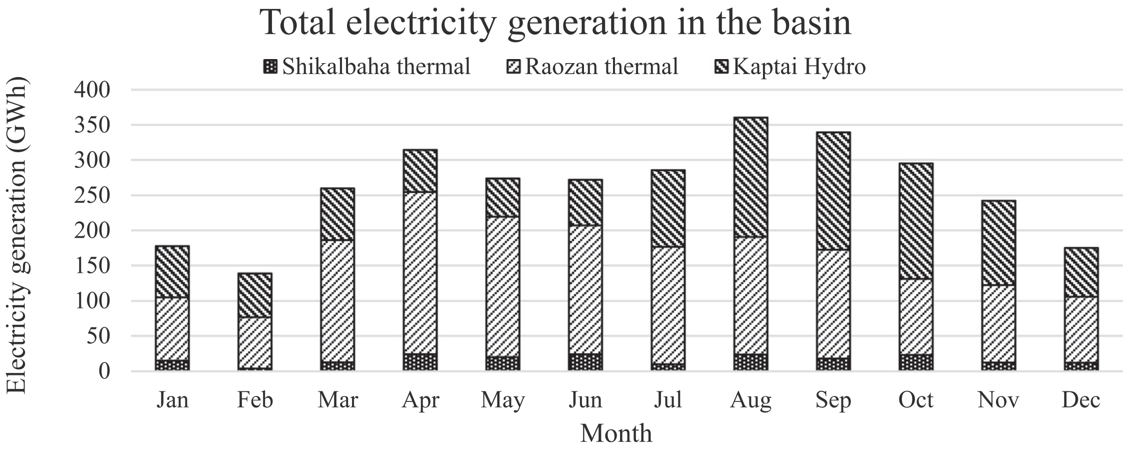

Fig. 6. Monthly power production from different sources in Karnafuli River Basin.

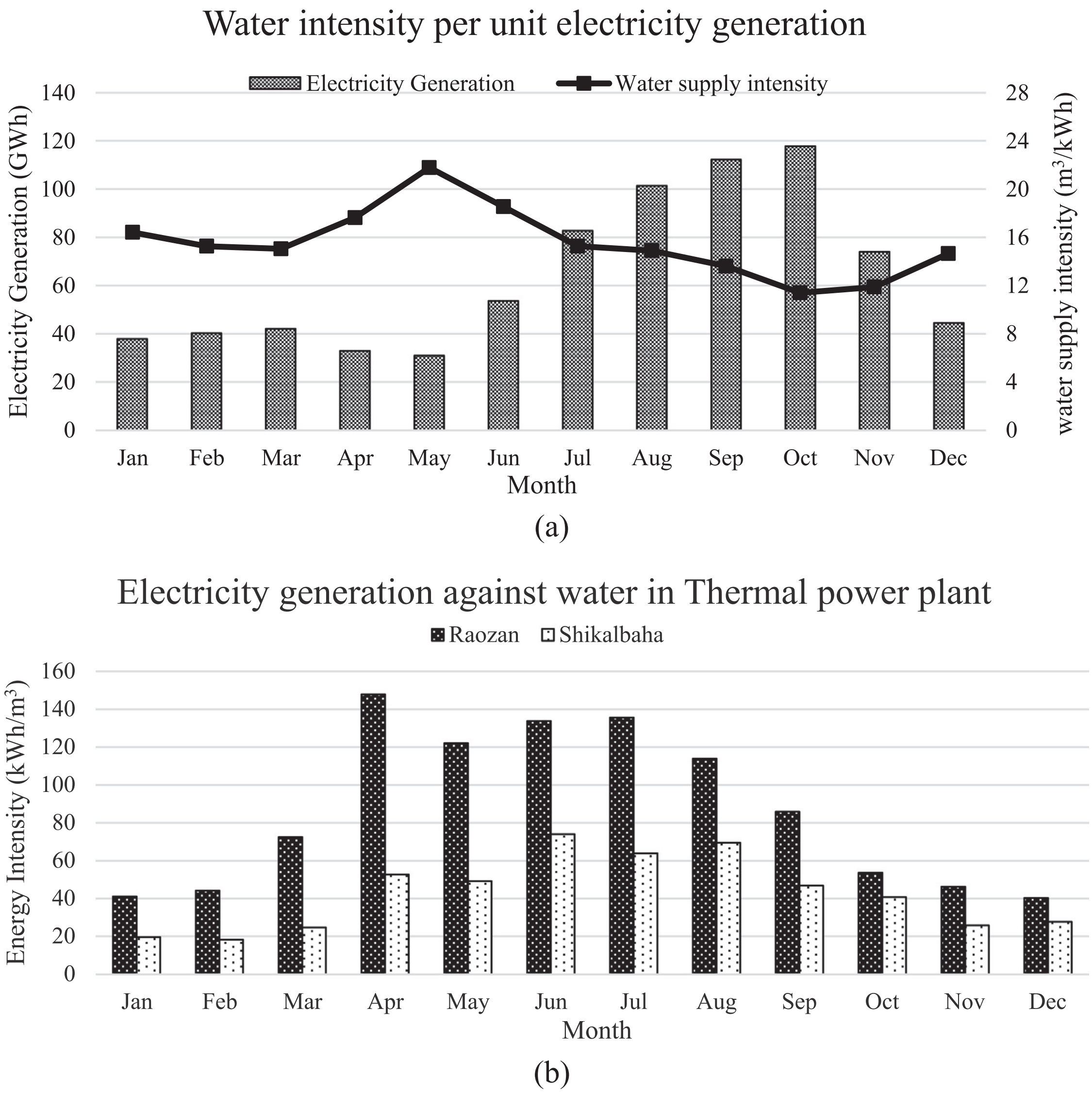

Fig. 7. (a) Water intensity of Kaptai hydropower plant, (b) Energy intensity of thermal power plants in Karnafuli River Basin.

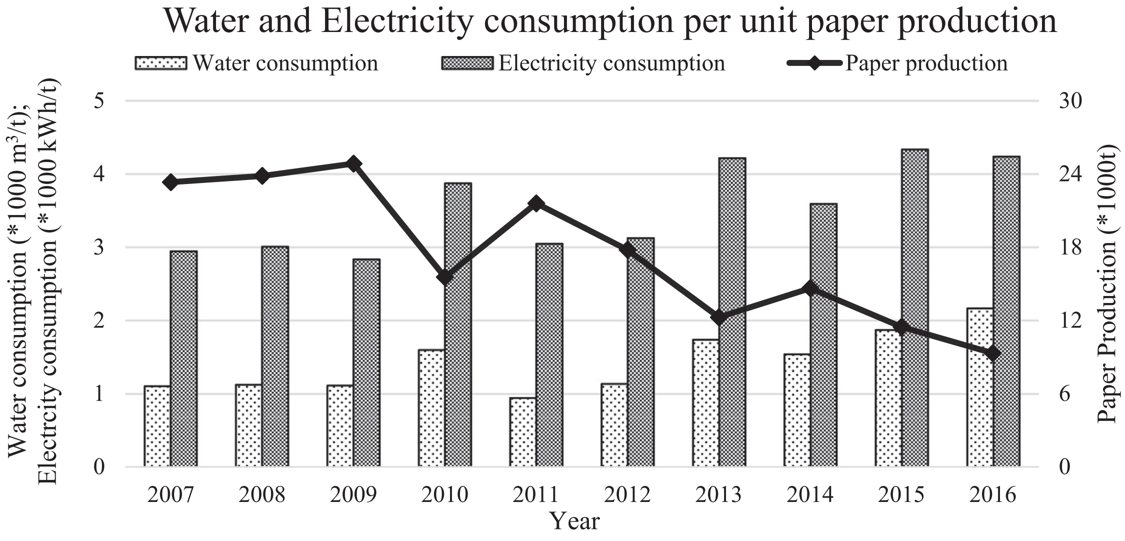

Fig. 8. Total paper production with water and electricity consumption in Karnafuli Paper Mill.

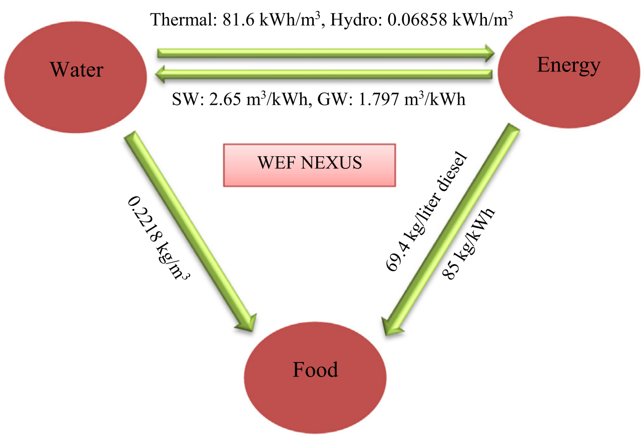

Fig. 9. Water energy and food resources interaction in the Karnafuli River Basin.

Table 5
Monthly net economic return from unit volume of water supplied (US$/m^3).

Month	Domestic	Agriculture	Energy	Industry	Hydropower	Environment
Jan	0.05387	0.0077	0.230	0.736	0.00059	0.00216
Feb	0.05724	0.0069	0.246	0.702	0.00064	0.00216
Mar	0.05181	0.0065	0.400	0.685	0.00065	0.00216
Apr	0.05201	0.0050	0.818	0.668	0.00055	0.00216
May	0.05271	0.0050	0.678	0.706	0.00045	0.00216
Jun	0.05285	0.0050	0.753	0.717	0.00080	0.00216
Jul	0.06986	0.0206	0.758	0.770	0.00097	0.00216
Aug	0.0701	0.0206	0.644	0.771	0.00099	0.00216
Sep	0.07182	0.0206	0.483	0.788	0.00108	0.00216
Oct	0.06824	0.0213	0.307	0.767	0.00129	0.00216
Nov	0.07122	0.0077	0.261	0.710	0.00124	0.00216
Dec	0.04815	0.0077	0.230	0.753	0.00067	0.00216

3.2.4. *Energy in food production*

In the Ichamati unit, the total electricity consumed from 2007 to 2016 was 3,207,960 kWh to produce 272,790 tons of raw crops. In the Halda unit, water is supplied through canal with no electrical pumping required. Thus, the raw crop produced per unit of energy consumed is 85 kg/kWh in the basin. Likewise, the total amount of diesel used in Ichamati unit and Halda unit from 2007 to 2016 was 16,569,060 liters to produce 1,149,810 tons of raw crops. Therefore, 69.4 kg of the raw crop is produced per liter of diesel in the basin. The energy consumed per crop production is low in the Karnafuli basin mainly due to the reason that water is supplied through pumping only from December to June in Ichamati unit, while rainwater is the source of irrigation for the rest of the month.

3.3. *Net economic return of different sectors*

The net economic return is essential for the econometric analysis of water allocation. The Karnafuli reservoir releases water for hydropower generation through the Kaptai dam, and the amount of water that passes through the turbine alone produces electricity. Since the agriculture sector demand is higher than the other sectors, desalination of water for agriculture use though not a common practice, is assumed to determine how much has to be spent on upgrading water quality. The NER of water to the environmental sector (salinity control) is estimated at US$ 0.00216/m^3. The net economic return for domestic, energy, agriculture, and industry sectors are presented in Table 5.

3.4. *Optimization of economic return*

The economic return for different water allocation scenarios is compared with respect to the actual withdrawals under the current allocation practice, as illustrated in Table 6. According to the existing situa-

Table 6
Comparison of ER for different water allocation scenarios (yearly basis).

Sector	Demand	Scenario 0			Scenario 1			Scenario 2			Scenario 3								
											Scenario 3.1			Scenario 3.2			Scenario 3.3		
	MCM	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)
Hydropower	11,289.5	11,289.6	100.0	10.2	11,289.5	100.0	10.2	11,289.6	100.0	10.2	11,289.6	100	10.2	11,289.5	100.0	10.2	11,289.6	100.0	10.2
Domestic	85.0	33.6	39.5	2.01	102.0	100.0	6.1	127.6	100.0	7.6	85.0	100	5.1	102.0	100.0	6.1	127.6	100.0	7.6
Agriculture	782.2	518.4	66.3	5.2	938.6	100.0	9.3	1173.3	100.0	11.6	782.2	100	7.7	938.6	100.0	9.3	1173.3	100.0	11.6
Energy	12.0	12.0	100.0	5.8	14.4	100.0	6.9	18.0	100.0	8.7	12.0	100	5.8	14.4	100.0	6.9	18.0	100.0	8.7
Industry	26.5	26.5	100.0	19.3	31.8	100.0	23.2	39.7	100.0	29.0	26.5	100	19.3	31.8	100.0	23.2	39.7	100.0	29.0
Environment	8870.1	8695.9	98.0	18.8	9461.9	88.9	20.4	10,524.2	79.1	22.7	8515.4	90.1	18.3	9461.9	88.9	20.4	10,524.2	79.1	22.7
Total	**9775.9**	**9286.5**	**95.0**	**61.3**	**10,548.8**	**89.9**	**76.2**	**11,882.8**	**81.0**	**89.9**	**9421.2**	**96.4**	**66.6**	**10,548.8**	**89.9**	**76.2**	**11,882.8**	**81.0**	**89.9**

Scenario 4									**Scenario 5**								
Scenario 4.1			Scenario 4.2			Scenario 4.3			Scenario 5.1			Scenario 5.2			Scenario 5.3		
Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)	Water allocation (MCM)	Satisfaction (%)	TER (million US$)
11,289.6	100.0	10.2	11,289.6	100.0	10.2	11,289.6	100.0	10.2	10,901.2	96.6	9.7	10,901.2	96.6	9.7	10,901.2	96.6	9.7
85.0	100.0	5.1	51.4	50.4	3.3	53.5	41.9	3.5	85.0	100.0	5.1	102.0	100.0	6.1	127.6	100.0	7.6
427.5	54.7	5.4	366.3	39.0	5.5	367.5	31.3	6.4	782.2	100.0	7.7	938.6	100.0	9.2	1173.3	100.0	11.6
12.0	100.0	5.8	7.3	50.4	4.4	7.5	41.9	4.4	12.0	100.0	5.8	14.4	100.0	6.9	18.0	100.0	8.7
26.5	100.0	19.3	15.8	49.6	11.8	16.3	41.0	12.4	26.5	100.0	19.3	31.8	100.0	23.2	39.7	100.0	29.0
8870.1	100.0	19.1	10,081.4	94.7	21.7	11,298.5	84.9	24.4	7862.7	88.6	16.9	8496.2	79.8	18.3	9387.2	70.6	20.2
9421.2	**96.4**	**65.1**	**10,522.2**	**89.7**	**57.1**	**11,743.3**	**80.1**	**61.5**	**8768.5**	**89.7**	**64.7**	**9583.1**	**81.7**	**73.7**	**10,745.9**	**73.3**	**87.0**

tion, the total demand is 4094.5 MCM which can meet 91.3%, whereas the deficiency is 354.7 MCM. With the existing demand, the total net economic return is at US$ 21.766 million, including US$ 1.925 million from the hydropower sector. If it is supplied according to each sectoral demand with the available water, the maximum NER can be US$ 23.534 million.

Following the optimization function of maximizing ER, increasing demand brings more ER, although the satisfaction level will decrease. A sector's satisfaction level is defined as the ratio of the amount of water supplied to the sector's normal demand. When there is no priority imposed, the water is allocated to the sector with the highest NER value, the second-highest, and so on. After fulfilling those demands, water is allocated for salinity control as it provides the least ER.

When water allocation for the agriculture sector is the first priority, followed by industry, energy, domestic, and environment sectors, the ER for the three scenarios is estimated as US$ 23.5, 26.2, and 30.3 million. However, the satisfaction level decreases (91.3%, 76.1%, and 60.9%) accordingly. Thus, prioritizing the agriculture sector has no effect on other sectors except the environment sector. The satisfaction levels in the environment sector for these scenarios have decreased significantly, which is 90.1%, 72.7%, and 55.2%, respectively.

When first priority is provided to the environment sector to control salinity, the ER is the least among other scenarios. In existing demand conditions, the ER value can be made US$ 22 million, and when demand increases to 20% and 50% more, not only is the NER decreased to US$ 10 million but also the satisfaction level is accounted as 87.1% and 69.7% respectively.

When the reservoir released water is reduced by 20%, in order to maximize the NER, the environment sector's satisfaction will also be reduced. The NER for the three cases is US$ 22.2, 24.9, and 28.9 million, whereas satisfaction levels are 76.1%, 63.4%, and 50.7%, respectively. And the environment sector's satisfactions are 72.7%, 58.2% and 43.6%.

A number of limitations and assumptions were considered in the basin. It includes the total amount of water released from the Karnafuli reservoir is considered as the available water to fulfill the downstream water demand of different sectors of the basin. The losses of Karnafuli river water through evaporation and groundwater infiltration are considered negligible. The hydropower plant with the reservoir has not been considered in the water user sector of the basin. In addition, the flow in the Ichamati River, a tributary of the Karnafuli river, is taken as negligible. Water and energy consumption in the food sector are considered only for raw crop production from the cropland without considering the consumption of resources, for example, in the food processing and value chain. Also, the water supplied to the Halda unit of the Karnafuli Irrigation Project is taken as 40% from the Karnafuli River and 60% from the Halda River. Downstream water requirement has been considered as

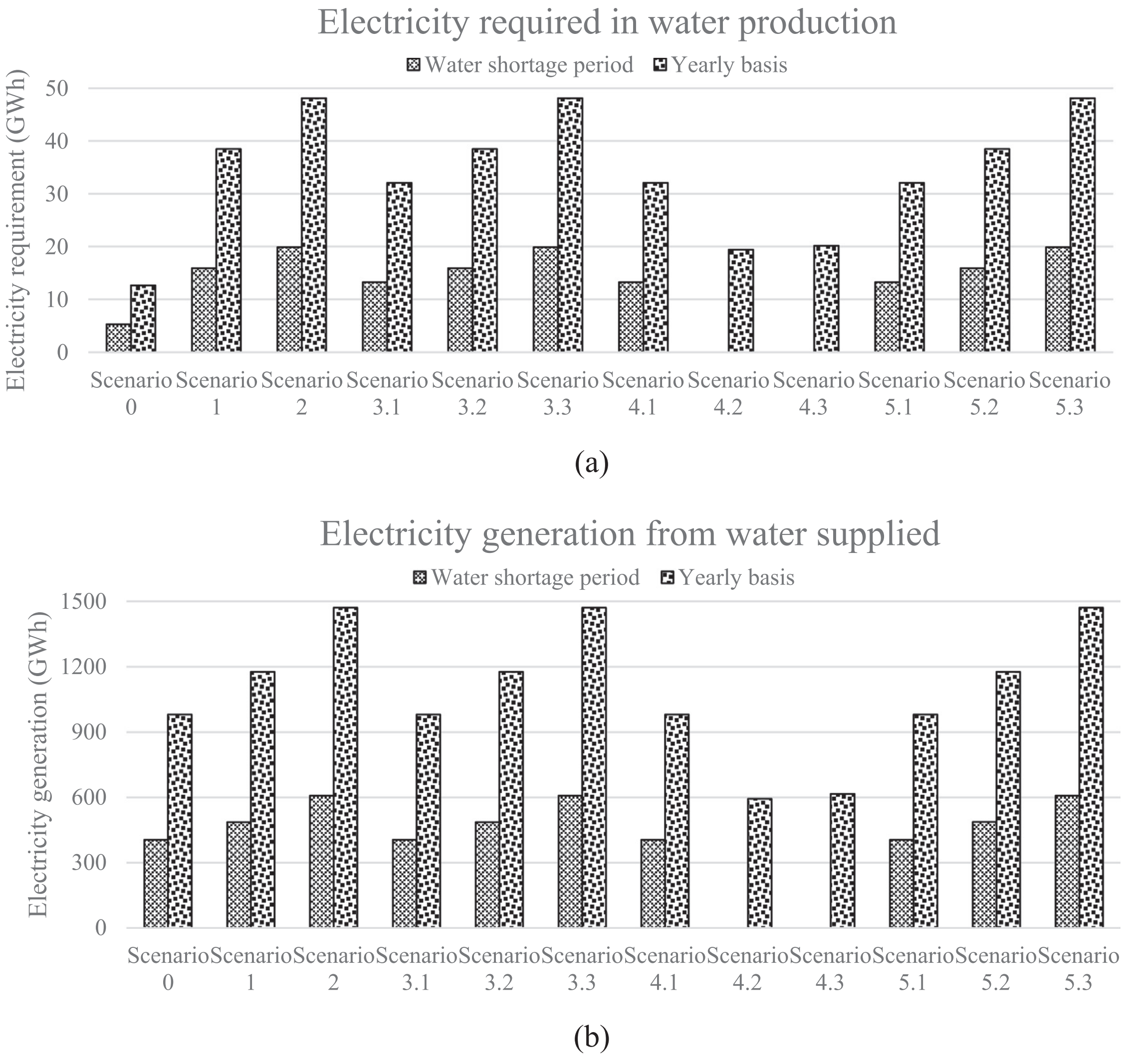

Fig. 10. (a) Electricity requirement in water production for different scenarios, (b) Electricity generation from water supplied for different scenarios, (c) Agricultural production from water supplied for different scenarios, (d) Diesel consumed in agriculture production.

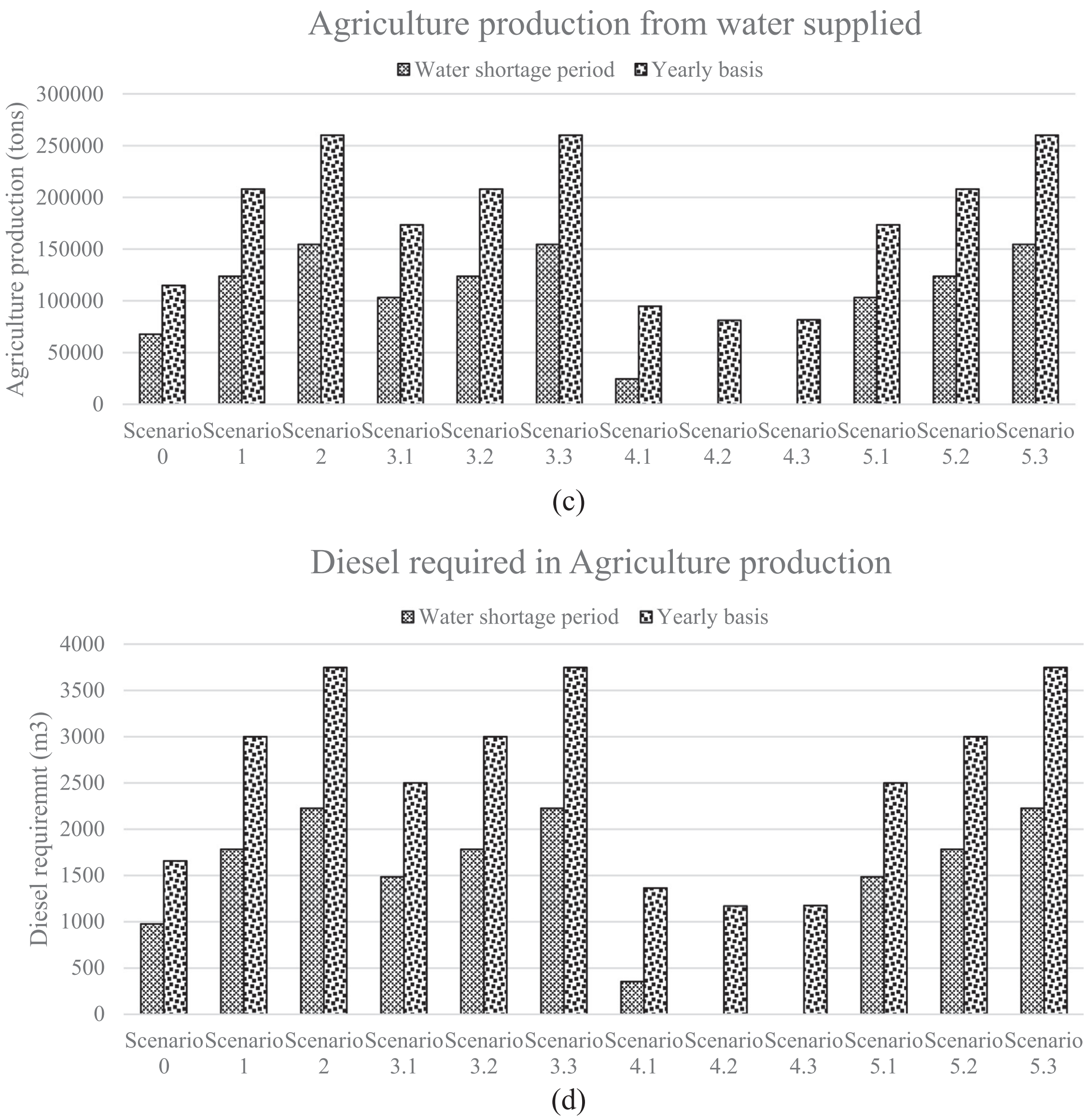

Fig. 10. Continued

salinity control which has been established from the result of the salinity model of IWM, Bangladesh.

3.5. Water energy food nexus indicators for scenarios analyzed

The scenarios analyzed in Section 3.4 have a different water allocated in each sector. With this different amount of water, the associated WEF nexus components are analyzed in this section.

In case when the demand of all sectors is increased by 20% (scenario 1), it is observed that the energy required in surface water and groundwater production increases by almost three-fold from 5 GWh to 15.9 GWh in the dry period and 12 GWh to 38.48 GWh annually (Fig. 10a). In contrast, not much increase in energy generation is observed (Fig. 10b). In the case of the food sector, about a two-fold potential increase in agriculture production from 67,793 tons to 123,770 tons in the dry period and 114,976 tons to 208,193 tons can be gained (Fig. 10c) however, the energy requirement in agriculture increases by two-fold as well (Fig. 10d). When the demand of all sectors is increased by 50% (scenario 2), it is observed that a maximum of 19.895 GWh of energy in the dry period and 48.092 GWh annually is required in surface water and groundwater production, which is about a four-fold increment from the existing condition. Likewise, with the increase in demand of all sectors by 50%, the maximum electricity that can be generated in the basin is 608.4 GWh in the dry period and 1470.5 GWh annually. The maximum agriculture production that can be gained is about 154,712 tons in the dry period and 260,241 tons annually, along with the increase in energy requirement in agriculture production when the demand of all sectors increases by 50%.

When the water allocation for the agriculture sector is given first priority (scenario 3) with the demand of all sectors increased by 20% and 50% (scenarios 3.2 and 3.3), it is observed that the water, energy, and food resources production and consumption follow the same results as that of scenario 2, when the demand is increased by 50%. This means that, regardless of whether the agriculture sector is given first priority or not, this doesn't bring any changes in the outcome of water energy and food resources production and consumption in the basin. On the contrary, when the environment sector is given first priority (scenario 4) with the demand of all sectors increased by 20% and 50% (scenarios 4.2 and 4.3), it is observed that the basin doesn't have sufficient water to meet the demand in other sectors during the dry period, thus affecting the annual energy generation as well as water production by half in comparison to existing demand condition (scenario 4.1) (Fig. 10a, b). In fact, even with the existing demand condition (scenario 4.1), the maximum agriculture production will be 94,820 tons which is less than half of the production in scenarios 2 and 3 (Fig. 10c). Water allocation for scenarios 3 and 5 is the same, thus the observed analysis is the same in scenario 5 as that of scenario 3.

4. Conclusions and suggestions

This study successfully evaluates the existing situation of the water, energy and food resource interaction in the Karnafuli River Basin using a set of indicators and develops an optimization model that allocates water to different water user to find the maximum economic return under different socioeconomic development scenarios. The findings can be summarized as follows: (1) The Kaptai hydropower plant in the basin requires 14.58 m^3 of water to generate 1 kWh of energy in comparison to the thermal power plants which consume only 0.012 m^3 of water to generate 1 kWh of energy; (2) Water consumed to produce 1 ton of crop in the basin was three times higher than the global average of 1486 m^3/ton [34]; (3) A maximum economic return of US$30.3 million can be generated in the basin however, at the cost of the environment sector being satisfied with only 55.2% of its water demand.

Results obtained from this study contribute to providing essential information and tools that assist in improved understanding of the water-energy-food situation in the Karnafuli River Basin and the influencing factors affecting it. These findings hold significant implications for decision-makers with regards to the establishment of an effective water resource planning and management in the Karnafuli River Basin from the following aspects: (1) The findings reveals that there lies a trade-off between maximizing economic benefits and sustainable water resources use in the basin, thus, development of the integrated water resource planning and management system to strengthen coordination among the water use sectors for optimal water allocation is essential to improve synergies between competitive users and meet the growing demand in the basin; (2) Urgent effort towards improving and developing irrigation networks, capacity building for farmers, agricultural techniques and technologies for enhancing water use efficiency and productivity is necessary in the basin; (3) The study indicates a potential of 12.87 GWh of energy could be conserved within the basin by decreasing the dependence on groundwater as the predominant water source and enhancing the efficiency of water supply services. This can be attained through several means, including the provision of providing alternative sources of water such as rainwater harvesting, adopting smart metering and monitoring techniques for groundwater usage, leveraging artificial intelligence techniques to detect leakages and minimize non-revenue water losses in utilities, increasing public awareness to educate citizens on water conservation and the adverse effects of over-exploitation of groundwater resources, and implementing regulatory policies to govern groundwater use and incentivize the use of alternative sources of water in the basin.

It is important to note that some uncertainties are inherent while applying the indicator-based approach to assess the water-energy-food nexus situation in the Karnafuli River Basin. Often, uncertainty is introduced in the selection of indicators itself [3,6,39]. Moreover, certain assumptions and considerations further propagate these uncertainties at different levels of assessment which is primarily driven by data availability. For example, in this study, water and energy consumption in food production represents only raw crop production without considering the consumption of these resources in the food processing industries and value chain.

Likewise, energy consumed in treating wastewater is not considered while evaluating the energy consumed for surface water production indicators. Similarly, the study assumes the total amount of water released from the Karnafuli reservoir is considered as the available water to fulfill the downstream water demand of different sectors in the basin. Thus, this may result in some underestimation or overestimation of these resource consumption. Moreover, food waste for biofuel production could also be incorporated into future research to take into account the interaction of food for energy production. Thus, some measures to quantify such uncertainties should be emphasized in future research.

CRediT authorship contribution statement

Mukand S Babel: Conceptualization, Methodology, Writing –review & editing. **Mostafizur Rahman:** Conceptualization, Methodology, Formal Analysis, Data collection, Writing –review & editing. **Aakanchya Budhathoki:** Methodology, Validation, Writing – original draft, review & editing. **Kaushal Chapagain:** Methodology, Validation, Writing – original draft, review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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