



Mathematical modelling for the phosphate and nitrate carrying capacity of dams in Uttarakhand

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ABSTRACT

The Himalayan State of Uttarakhand has abundant natural water resources and 98 Hydro Electric Power Project (HEP's) have been constructed, 25 are under construction and, 336 are planned for the future. The water bodies of these HEP's can also be utilized for other purposes besides electric power generation. To conserve the endemic aquatic biodiversity, it is necessary to understand the phosphate and nitrate dynamics of these water bodies. As there are several HEP's on a single river and the human population around them, water bodies have changed drastically during the last decade. In this study, we have calculated the phosphate and nitrate load-carrying capacity of six dams in the Uttarakhand state of India using the Vollen-Weider mathematical model modified by Dillon, Rigler and Beveridge. We have also measured the phosphate & nitrate content of these water bodies to confirm if our modelling methods confirmed with actual finding of sampling sites. The phosphate and nitrate carrying capacity of these six dams were found to be in the range of 0.155 mg/l to 0.557 mg/l and 0.6 mg/l to 1.3 mg/l. To the best of our knowledge, this is the first study in Uttarakhand that addresses the phosphate and nitrate carrying capacity using a mathematical model.

Introduction

Phosphate and nitrate are useful nutrients, but they can cause difficulties in our water environment if they get excessively concentrated. In aquatic ecosystems, phosphorus is commonly referred to as the "limiting nutrient," meaning that the amount of this nutrient available determines the rate at which algae and aquatic plants are produced. Phosphate is the most frequent type of phosphorus used by biological organisms, and it is essential for the creation of DNA, cellular energy, and cell

membranes (and plant cell walls). While largest source of nitrate in water body is decomposing legumes, but high nitrate concentrations can also be created by human or animal wastes and fertilizer run-off. Although it is necessary for plant growth, excessive amounts in water can hasten eutrophication (a decrease in dissolved oxygen in water bodies caused by an increase in minerals and organic materials) in water bodies (Hampel *et al.*, 2018; LeMoal *et al.*, 2019). Soil erosion is a key

source of phosphorus in water bodies (Rickson, 2014). However, because phosphorus and nitrate is found in small amount in nature, even small increases can have a deleterious impact on water quality and biological circumstances.

In aquatic systems, the phosphorus is mainly deposited in sediment showing its affinity towards particles (Saraswathy *et al.*, 2019). The majority of phosphorus in sediment is integrated into sediment organic matter (Holtan *et al.*, 1988). There are various physicochemical properties of sediments that control the trapping and release of phosphorus into the water like hydrological dynamics, and biological activity (Orihel *et al.*, 2017). The hydrodynamics of the dam advance the formation of inner sedimentary phosphorus load; hence 12% of the global aqueous phosphorus is conserved in it (Orihel *et al.*, 2017). Surface waters in most comparatively uncontaminated lakes have been found to have 0.03 to 0.09 mg/l phosphate (Fadiran *et al.*, 2008). Phosphate levels as low as 0.08 mg/l in water bodies, on the other hand, can induce excessive or bothersome growths of algae and other aquatic plants during the spring when nutrients are cycling to the surface. Because flowing water are less vulnerable to rapid or cultural eutrophication, a phosphate concentration of less than 0.3 mg/l is the intended target for them. The maximum nitrate content in the water that can be tolerated is 10 mg/l, anything above can have negative consequences and contribute to nitrate water pollution (Camargo *et al.*, 2005). The depth and kind of water body, as well as the type of soil, land use, and the age of the groundwater, all influence the contamination of water bodies (Canada, 1997). It's critical to comprehend how these numerous aspects will affect the poisoning of various water sources. In general, nitrate content drops as depth increases, making surface water significantly more vulnerable to nitrate pollution (Almasri and Kaluarachchi, 2004). Nitrate toxicity levels are also significantly lower in larger bodies of water, but they are much higher in smaller and shallower bodies of water because nitrate concentrations are simpler to build up (Camargo *et al.*, 2005).

Dam construction and the dam itself have variable impact- social, economical, geographical and impacts on water quality, climate, flora and fauna. Various man-made pressures are associated with

water bodies. These activities can be at the local level (drainage & local activities), at the regional level (energy demands, drinking water, commercial activities, etc.) and, at the global level due to climate change (Richardson *et al.*, 2018). Of these, the effect caused at the local and regional level had the highest impact on the structure and function of water bodies (Maberly *et al.*, 2020). Water biodiversity is highly affected by these anthropogenic pressures (Zhang *et al.*, 2019). With growing water stress and energy demand, the number of dams has increased and will continue to increase in the future too. The construction of dams greatly modifies the ecological functioning of the water body system. The natural flow of water is interrupted by the dams, causing a reduction in the velocity of water and expanding the residence time of water. Due to this the stream competence is restricted in reservoirs, encouraging the accumulation of sediment. Moreover, the fine fraction of sediments are present in the surrounding dam (López *et al.*, 2016), increasing nutrient levels (Le Faucheur *et al.*, 2016). Since aquatic ecosystems have a limited capacity to remove incoming phosphorous and nitrogen load, they need intervention to limit nitrate threat.

The Uttarakhand state of India is located in the Himalayan region of North India and has a total area of 53483 sq. km. of which 38000 sq. km. is forest area and 4060 sq. km. area is covered by glaciers (India state of forest report 2019). Because of abundant water resources, the state started on an ambitious journey of hydropower regeneration. Uttarakhand has a total of 98 existing hydropower projects (HEPs), with a total installed capacity of close to 3600 Megawatt (MW) and 25 projects with 2376.3 MW capacities are under construction in Uttarakhand (Uttarakhand Jal Vidyut Nigam Limited UJVN Limited). According to reports, a total number of 459 dams are existed or under construction and are planned for the future within 300 miles radius in Uttarakhand (Uttarakhand Jal Vidyut Nigam Limited UJVN Limited). Some projects have suffered damage due to the flash flood disasters in Uttarakhand (Uttarakhand Jal Vidyut Nigam Limited UJVN Limited), the most recent one being the Rishi Ganga project in 2021. The astounding number of HEPs gives us an idea about the level of anthropogenic activities on water bodies. Hence, it is necessary to understand the phosphate

and nitrate dynamics of water bodies. We have calculated the phosphate and nitrate load capacity using a mathematical model and also measured phosphate and nitrate for selected water bodies. More comprehensive monitoring of phosphate and nitrates in water bodies accompanied by the implementation of water policy regulations will help in combating phosphate and nitrate threat to water quality.

Material and Methods

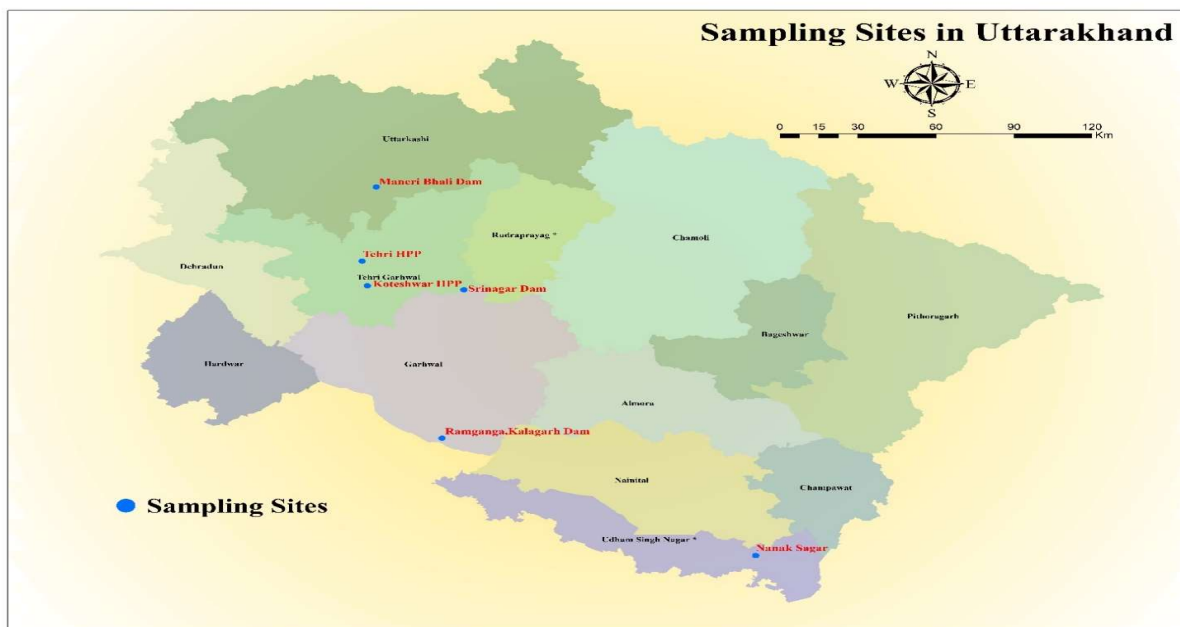


Figure 1: Map showing the location of six dams (a to f). (a) Nanak Sagar dam, (b) Koteswar dam, (c) Ramganga dam, (d) Srinagar dam, (e) Tehri HPP, and (f) Maneri dam.

In this paper, we used several parameters, the length of the dam, gross storage capacity, area of the dam, effective storage capacity, and the variation in concentration of phosphate $[P]_i$ for the mathematical calculation of total $[P]_i$ carrying capacity. The data used for calculation in the mathematical model were retrieved from the National Register for Large Dams (NRLD). The data were obtained from government websites/online portals.

Carrying capacity analysis

The carrying capacity analysis of all the dams was done by analyzing the quality of water and by calculating the capacity of pollution load in the dams for the activity of aquaculture. The tools used for the estimation of water quality along with the standard as in Methods for Examination of Water and

Study sites:

For the present comparative study, we selected six study sites that are already constructed dams in Uttarakhand viz. Nanak Sagar, Koteswar, Ramganga, Srinagar, Tehri, and Maneri (Figure 1). The state of Uttarakhand is recognized for its various rivers, sacred temples, and places, located on the banks of rivers. These rivers originate from glaciers of the western Himalayas situated in the borders of India, Nepal, and China.

Wastewater (America Public Health Association 1992).

Data analysis of physicochemical characteristics

The main reason to study the chemical, physical parameters of water is to examine its nutrient status. Since the water has suspended and dissolved materials in many amounts its chemical and physical parameters differ along with its biological properties (Table 1). There are other reasons also due to which water is affected like pollutants and acts on elements present in water e.g. pH, TDS, Turbidity, Alkalinity, Phosphate, Nitrate, etc. (Table 3). Without the knowledge of the chemistry of water, it is not possible to understand the biological phenomenon fully.

Table 1: General overview of six dams of Uttarakhand

Name of Dam	Nanak Sagar	Koteshwar HEP	Ramganga	Srinagar	Tehri HPP	Maneri
Longitude of dam	79°45' E	78°29'52" E	78°45' E	78°49'20.41" E	78°28'44" E	78°32' E
Latitude of dam	28°45' N	30°15'36" N	29°31' N	30°14'31.28" N	30°22'41" N	30°44.5' N
Length of Dam (m)	19200.00	300.50	715.00	248.00	27980.00	13.70
Gross storage capacity (10 ³ m ³)	209000.00	889000.00	244960.00	78000.00	3540000.00	600.00
Reservoir Area (10 ³ m ²)	50000.00	3022.00	19720.00	4500.00	44000.00	180.00
Effective storage capacity (10 ³ m ³)	200550.00	35000.00	218770.00	8000.00	2615000.00	510.00
Designed spillway capacity (m ³ /sec)	1600	13290	8467	19200	13000	5000

Source: National Register of Large Dams | Central Water Commission, Ministry of jalshakti, Department of Water Resources, River Development and Ganga Rejuvenation, GoI (cwc.gov.in).

Statistical analysis

In this section, we performed statistical analysis to calculate the mean, standard deviation, and standard error from samples obtained from six dams in the months of April, August, and December 2021. The obtained results are discussed in Table 2, and the numerical mean values of the phosphate and nitrate levels have been used in the mathematical modeling. The phosphate and nitrate Q-value curve for generating a water quality index, as shown in (Figure 2), illustrates the impact of phosphate and nitrate levels on water quality. The q-value curve for phosphate and nitrate, which is used to calculate a water quality index, shows that water quality degrades rapidly as phosphate and nitrate concentrations rise.

Mathematical model

To define the carrying capacity, the Vollen-Weider model has been used in this research which has been modified by Dillon & Rigler.

- Considering the P concentration (mg m⁻³) in water as a function of the annual P load (L_f , in mg m⁻² year⁻¹), the P retention coefficient (R_f), average depth (z , in meters), and water flushing rate (ρ , in years),
- The amount of phosphate total endured forever by sediment (x),
- The proportion of dissolved total phosphate can be holdout by the sediment (R).

In the fish production carrying capacity analysis model made by (Dillon and Rigler 1974), there are total 5 steps:

➤ Step 1:

The capacity of aquatic for fish in accepting phosphorus or total P concentration ($\Delta [P]$) is the mean of the phosphate level in the dam (Table 2).

➤ Step 2:

Next, we determine R for the dam, where R is the P retention coefficient from the study by (Larsen and Mercier 1976), with modifications by (Canfield and Bachmann 1981).

To calculate the value of R we have used the equation.

$$R = \frac{1}{1+0.747*\rho^{0.507}} \quad (1)$$

➤ Step 3:

The amount of phosphate produced by fish is calculated by

$$R_f = x + [(1 - x) * R]. \quad (2)$$

➤ Step 4:

Next, calculate the pollution load capacity of fish in the dam is given by the equation.

$$L_f = \frac{\Delta[P]*z*\rho}{1-R_f}, \quad (3)$$

where $\Delta[P]$ is mean phosphate level in dam, z is the depth of dam

$$\left(z = \frac{V_G}{R_a}, V_G \text{ is the total volume and } R_a \text{ is the area of the dam} \right)$$

and ρ is the flushing rate

$$\left(\rho = \frac{S_w}{V}, S_w \text{ is the spillway capacity and } V \text{ is the effective storage capacity of dam} \right).$$

➤ **Step 5:**

The total carrying capacity of fish production in the dam allowed maximum pollution load can be determined by

$$TC_{cap} = L_f * A, \quad (4)$$

Where A is the area of the dam (Bueno *et al.*, 2017).

Note: The same analysis has been performed for nitrate pollution load capacity (Replacing $\Delta[P]$ by $\Delta[N]$ in Step 1).

Results and Discussion

In this study, a total of six dams were taken and their maximum pollution load capacity (Ton. year⁻¹) was calculated based on the amount of phosphate total endured forever by sediment (which is presented by x), where the value of x is around 0.45 to 0.55 (Warningsih *et al.*, 2016). The Srinagar dam was found to have the largest phosphate pollution load capacity, indicating that it can contain up to 7340.14 tonnes of phosphorous waste every year. Warningsih (2016) found that the phosphate load capacity of the koto panjang reservoir is 225.933,851 tonnes per year, while the highest nitrate pollution load capacity was found in the koteshwar dam, indicating that the capacity of the koteshwar dam to hold nitrogenous waste is maximum 31105.90 tonnes per year. The pH of water is an important water quality indicator as it acts as a major factor in most chemical and biological reactions. The pH of the all six dams observed in the range of 7.58-7.81. Total dissolved solids (TDS) content has long been used as a measure of aquatic ecosystem productivity. Higher levels of TDS in bodies of water are generally harmful to aquatic life. TDS alters the mineral composition of water, which is critical for many species' existence. In addition, dissolved salt can dry aquatic animals' skin, which can be lethal. It can raise the temperature of the water, making it uninhabitable for many species. The TDS of all six recorded in the range of 48 mg/l-102 mg/l (Table 3). The turbidity of water is a measurement of how clear it is. High turbidity indicates that there are many particles suspended in the water that prevent light from passing through. The turbidity recorded all dams are in the range from 0.28 mg/l- 0.42 mg/l. A water body with a high alkalinity level has more calcium carbonate, or CaCO₃, which can reduce the acidity of the water. Alkalinity and water hardness are comparable in that they both arise from natural

sources. Water moves through rocks (and picks up minerals as it does so) on its way when limestone and dolomite dissolve in water, one half of the molecule is calcium or magnesium (the "hardness") and the other half is the carbonate (the "alkalinity"). The data on total alkalinity of water samples of six dams is given in (Table 3). The value of total alkalinity was found in all dams ranges from Tehri dam 22 mg/l- 64 mg/l. Hardness observed in all dams ranges from 28 mg/l-86 mg/l. Phosphate amount from the reservoir site is an important factor to determine as it is released due to the decomposition of aquatic vegetation. Phosphate value is minimum in the month of winters as it is utilized immediately by the overgrowth of phytoplankton. (Table 3) shows the levels of phosphate in different dams of Uttarakhand (Raveendar *et al.*, 2021; Singh *et al.*, 2020). The phosphate value recorded in all dams are in the range of 0.155 mg/l-0.557 mg/l. The data of Nitrate concentration of water samples of six different sites of the dam is given in (Table 3). Because of the significant use of algal groups and a low source of nitrate, the lowest concentration of nitrate was found in autumn. The nitrate value recorded in 0.6 mg/l-1.2 mg/l. Sulfur is used by aquatic organisms, and lower quantities have a negative impact on algae development. Sulfate is the most frequent type of sulphur found in well-oxygenated waters. Algal growth will not develop if the sulphate concentration is less than 0.5 mg/l. SO₄ value recorded in six dams are from 7 mg/l-14 mg/l. The F value observed from 0-0.14 mg/l. The occurrence of chloride (CL) is a major cause of water pollution that arises when salts from the soil are leached into water bodies. Although chlorides have only little impact on living organisms, their excessive consumption might cause considerable harm or poisoning. CL value of all six dams ranges from 1.3 mg/l-4.9 mg/l (Table 3). The use of the hydrodynamic model along with factorial bioenergetics models supports estimating the waste load and regulates the values used to calculate the carrying capacity of the reservoir for the production of fish. Total carrying capacity is directly proportional to the amount of phosphate and nitrate in the dam which means the total carrying capacity (TC_{cap}) of any dam is depends on the value of phosphate and nitrate available in the water of the dam.

Table 2: Statistical analysis of samples collected from six different dams in 2021

Phosphate						
MONTH	NANAK SAGAR	KOTESHWAR	RAMGANGA	SRINAGAR	TEHRI	MANERI
April	0.237	0.155	0.453	0.557	0.192	0.394
August	0.239	0.156	0.455	0.557	0.192	0.395
December	0.241	0.154	0.457	0.556	0.192	0.393
Mean	0.239	0.155	0.455	0.557	0.192	0.394
SD	0.002	0.001	0.002	0.0006	0	0.001
SE	0.0011	0.0005	0.0011	0.0003	0	0.0005
Nitrate						
April	1	1.2	1	1.2	0.7	0.65
August	0.9	1.4	1.2	1.4	0.8	0.6
December	0.8	1.3	1.4	1	1.05	0.55
Mean	0.9	1.3	1.2	1.2	0.85	0.6
SD	0.1	0.1	0.2	0.2	0.18	0.05
SE	0.0577	0.0577	0.1154	0.1154	0.1039	0.0288
pH						
April	7.58	7.79	7.65	7.64	7.82	7.77
August	7.57	7.78	7.63	7.68	7.81	7.76
December	7.59	7.8	7.61	7.66	7.8	7.78
Mean	7.58	7.79	7.63	7.66	7.81	7.77
SD	0.01	0.01	0.02	0.02	0.01	0.01
SE	0.0057	0.0057	0.0115	0.0115	0.0057	0.0057
TDS						
April	102	49	76	88	42	63
August	101	48	78	85	45	64
December	103	47	80	91	39	62
Mean	102	48	78	88	42	64
SD	1	1	2	3	3	1
SE	0.5773	0.5773	1.1547	1.7320	1.7320	0.5773
Turbidity						
April	0.4	0.39	0.39	0.42	0.28	0.31
August	0.45	0.36	0.4	0.43	0.27	0.31
December	0.35	0.33	0.38	0.41	0.29	0.31
Mean	0.4	0.36	0.39	0.42	0.28	0.31
SD	0.05	0.03	0.01	0.01	0.01	0
SE	0.0288	0.0173	0.0057	0.0057	0.0057	0
Alkalinity						
April	64	26	38	36	22	28
August	63	28	38	35	21	28
December	65	24	38	37	23	28
Mean	64	26	38	36	22	28
SD	1	2	0	1	1	0
SE	0.5773	1.1547	0	0.5773	0.5773	0
Hardness						
April	86	33	63	64	26	43
August	85	35	61	68	30	45
December	87	34	62	66	28	44
Mean	86	34	62	66	28	44
SD	1	1	1	2	2	1
SE	0.5773	0.5773	0.5773	1.1547	1.1547	0.5773
SO4						
April	15	ND	11	10	ND	6
August	14	ND	9	11	ND	7
December	13	ND	7	12	ND	8
Mean	14	ND	9	11	ND	7
SD	1	ND	2	1	ND	1
SE	0.5773	0	1.1547	0.5773	0	0.5773
F						
April	0.12	ND	0.14	ND	ND	ND
August	0.11	ND	0.12	ND	ND	ND
December	0.13	ND	0.16	ND	ND	ND
Mean	0.12	ND	0.14	ND	ND	ND
SD	0.01	ND	0.02	ND	ND	ND
SE	0.0057	0	0.011547005	0	0	0
CL						
April	5	2	2.8	2.9	1.3	2.4
August	4.9	1.9	2.9	2.9	1.3	2.3
December	4.8	1.8	3	2.9	1.3	2.2
Mean	4.9	1.9	2.9	2.9	1.3	2.3
SD	0.1	0.1	0.1	0	ND	0.1
SE	0.0577	0.0577	0.0577	0	0	0.0577

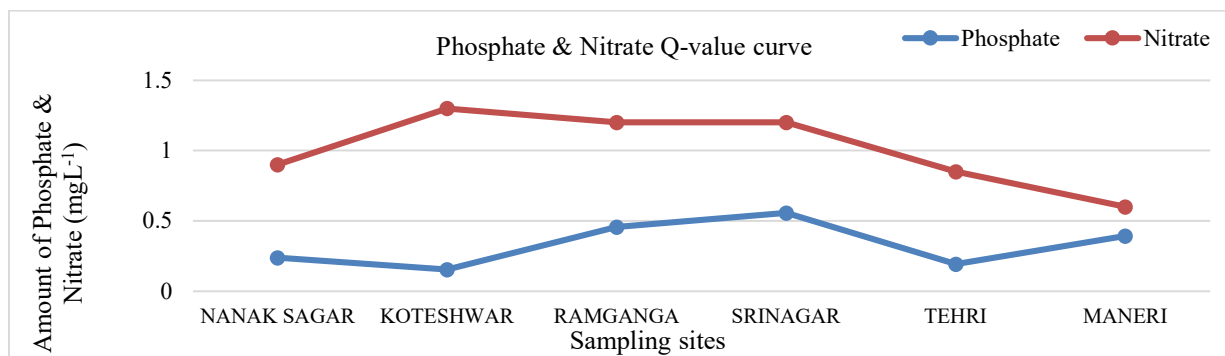


Figure 2: Amount of Phosphate and Nitrate in six dams of Uttarakhand

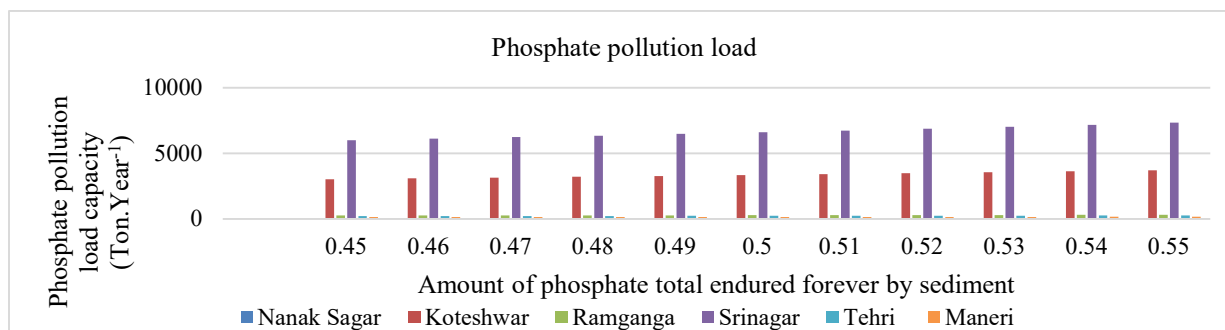


Figure 3: The maximum phosphate pollution load in six dams of Uttarakhand

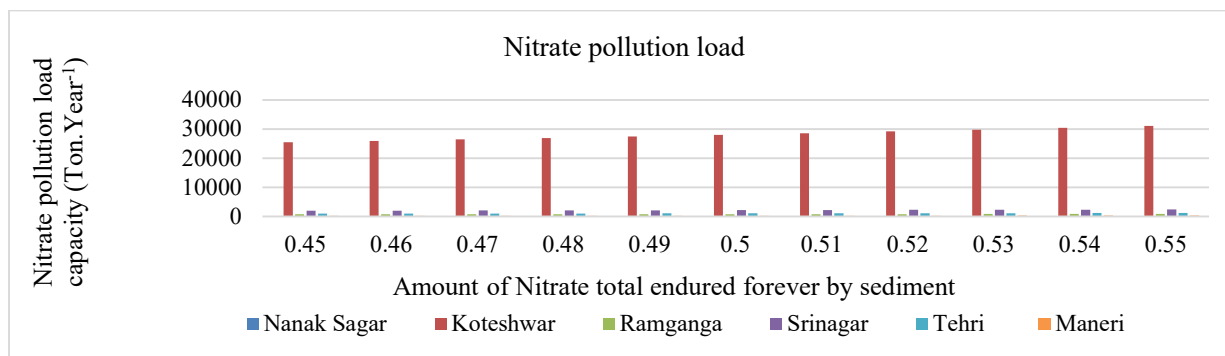


Figure 4: The maximum nitrate pollution load in six dams of Uttarakhand

Table 3: Average yearly analysis of different physicochemical parameters of six dams of Uttarakhand

Parameters	Nanak Sagar	Koteswar HEP	Ramganga	Srinagar	Tehri HPP	Maneri	Standard
pH	7.58 ± 0.01	7.79 ± 0.01	7.63 ± 0.02	7.66 ± 0.02	7.81 ± 0.01	7.77 ± 0.01	6-9
TDS (mg/L)	102 ± 1	48 ± 1	78 ± 2	88 ± 3	42 ± 3	64 ± 1	1500
Turbidity (NTU)	0.40 ± 0.05	0.36 ± 0.03	0.39 ± 0.01	0.42 ± 0.01	0.28 ± 0.01	0.31 ± 0.01	Below 1 NTU
Alkalinity (mg/L)	64 ± 1	26 ± 2	38 ± 1	36 ± 1	22 ± 1	28 ± 1	500
Hardness (mg/L)	86 ± 1	34 ± 1	62 ± 1	66 ± 2	28 ± 2	44 ± 1	500
Phosphate (mg/L)	0.239 ± 0.002	0.155 ± 0.001	0.457 ± 0.002	0.557 ± 0.0006	0.192 ± 0.001	0.394 ± 0.001	2
NO ₃ (mg/L)	0.9 ± 0.1	1.3 ± 0.1	1.2 ± 0.2	1.2 ± 0.2	0.85 ± 0.18	0.6 ± 0.05	10
SO ₄ (mg/L)	14 ± 1	ND	9 ± 2	11 ± 1	ND	7 ± 1	400
F (mg/L)	0.12 ± 0.01	ND	0.14 ± 0.02	ND	ND	ND	1.5
CL (mg/L)	4.9 ± 0.1	1.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	1.3 ± 0.1	2.3 ± 0.1	250

The availability of phosphorus in the water was significantly higher after fish mass mortality and harmed the water quality of Maninjau lake in Indonesia (Syandri *et al.*, 2017). In a case study of upper Itchen, (UK), some researchers monitored phosphorus for water quality management. It was suspected that recently increased phosphorus concentration was found in environmental degradation (Fones *et al.*, 2020).

A day after Typhoon Lekima swept across the coastal parts of Penang, Malaysia, in August 2019, mass fish mortalities were documented, resulting in massive losses among fish farmers. After the typhoon, the results showed abnormally low dissolved oxygen and high quantities of nitrate, nitrite, and chlorophyll a (Aileen *et al.*, 2021). In a pond environment in a rural setting in Central Kenya, the use of raw animal manure, high fish stocking density, high nitrates and nitrites, and high ammonia levels are all possible risk factors for fish mortality and the acquisition of infectious diseases (Wanja *et al.*, 2020).

Conclusion

By the vital examination of we analyze that for phosphate, Srinagar dam has the highest total carrying capacity (TC_{cap}), and for nitrate, Koteswar dam has the highest total carrying capacity (TC_{cap}). As this is a huge number, it means that even if we operate at half the maximum value, there is huge potential still available to develop commercial fisheries at these locations. Large numbers of hydroelectric power. Earlier water was flowing but now flow pattern has changed because of dams. These water bodies can be used but phosphate level is critical for an activity like commercial fisheries. All of the water quality parameters measured in this study were within acceptable limits for fish survival and growth. Maintaining nutrient levels in the dam through extensive aquaculture is critical to ensuring

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that product output does not suffer from deficient symptoms. In the hilly areas of Uttarakhand, there is a pressing need to switch to a different form of agriculture to increase productivity and create a distinct brand. Apart from hydropower generating and drinking water utilities, these reservoirs provide an excellent chance and area for adopting this type of agriculture and adding a new value to itself. Because of the well-connected highways surrounding the dam, any stakeholder or business may simply convey products into the market at a higher profit margin. It is high time for stakeholders and the government to take advantage of this tremendous resource to boost the economy and employment possibilities in and around the dam. Gradually, this might significantly reduce migration out of the area. Further study and development in this subject are critical for agro capitalism to flourish in Uttarakhand's migratory regions, which could be critical to the state's economic growth. As a result, embracing culture-based fisheries and minimizing intensive human activities could boost fish productivity of dam. This research will aid policymakers in the development of a reservoir management strategy. It was advised that the Ministry of Fisheries and Aquaculture Development and the competent authorities implement regulations of farming activities adjacent to the dam to ensure good water quality for the survival and growth of fish. Regularly monitoring the dam water quality will go a long way toward ensuring that aquatic resources are conserved and used sustainably. The government of Uttarakhand's efforts to expand domestic fish output through its "Aquaculture for food and jobs" initiative will be aided by the upkeep of water quality in dam.

Conflict of interest

The authors declare that they have no conflict of interest.

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