



Modeling of water hyacinth growth and its role in heavy metals accumulation from unoperated old Ganga canal at Haridwar, India

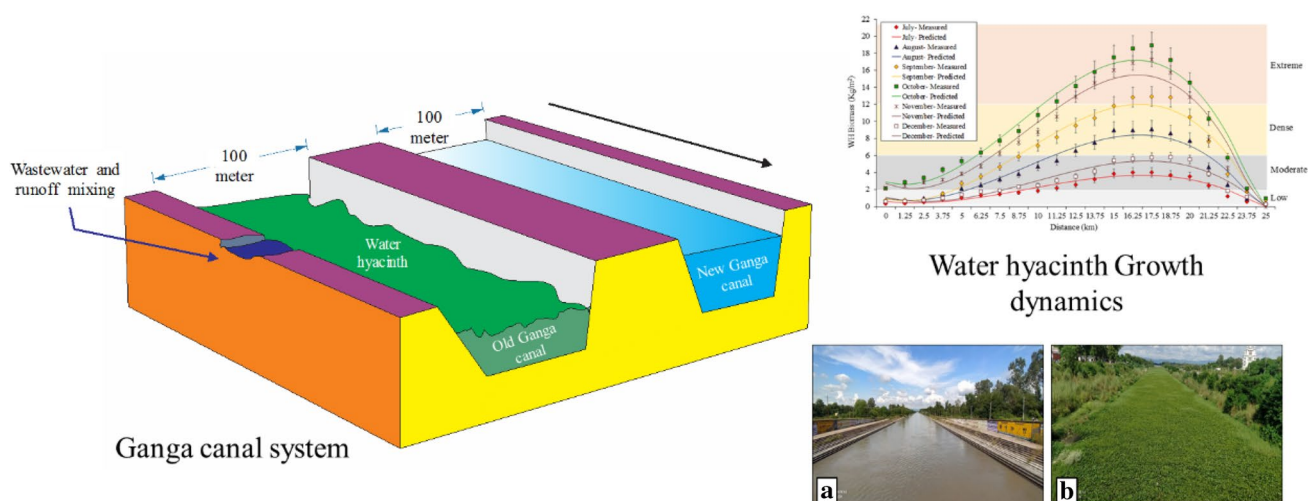
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Abstract

The present study aimed to investigate the annual potential of water hyacinth (WH; *Eichhornia crassipes*) macrophyte in an un-operated/abandoned stretch of the upper Ganga canal at Haridwar, India. The study covered a 25 km long and 100 m wide stretch of the old Ganga canal which exhibits a huge WH growth every year. For this, standard field and laboratory methods were adopted to estimate the WH biomass density (Kg/m²), and heavy metals dynamics between canal water and macrophyte biomass. Results showed that the average annual density of WH biomass was 5.538 kg/m² with significant ($P < 0.05$) heavy metals (HMs) accumulation as 1.50 mg/Kg dw of Cd, 0.21 of mg/Kg dw of Cr, 2.19 mg/Kg dw of Cu, 28.54 mg/Kg dw of Fe, 20.79 mg/Kg dw of Mn, and 9.39 mg/Kg dw of Zn, respectively. Using a polynomial cubic model, the annual trends of WH growth and HMs accumulation in both water and biomass were also simulated. The developed models showed good R² and error validation results that support the prediction criteria. The findings of this study revealed that WH's growth in the un-operated stretch of the old Ganga canal located at Haridwar has high HMs accumulation and biomass production potentials.

Graphic abstract



Keywords Ecological modeling · Heavy metals · Upper Ganga canal · Water hyacinth

1 Introduction

Pollution of freshwater bodies including rivers, lakes, wetlands, and ponds through wastewater disposal has become a serious cause of environmental degradation (Eid and

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Shaltout, 2017; ; Zare et al. 2020). In this, wastewater disposal containing a tremendous load of heavy metals (HMs) is one of the major causes of water body toxification (Renuka et al. 2014; Kumar et al. 2019b; Eid et al. 2021). As a result of the constant disposal of HM-holding wastewaters, fragile water bodies get easily contaminated. Subsequently, the contamination of surface water leads to disruption of the ecological food chain by bio-magnification of HMs from lower trophic levels to higher trophic ones (Bai et al. 2011; Li et al. 2020). Also, the aquatic biota, i.e., phytoplankton, zooplankton, benthos, fishes, amphibians, plant species, etc., are majorly affected by the altered toxicity of water bodies (Abrantes et al. 2006; Rai et al. 2013).

Besides this, certain plant species are adapted to grow in water bodies containing a high nutrient load called aquatic macrophytes (Kumar et al. 2019c; Thampatti et al. 2020). Such plant species play an important role in nutrient recycling through their translocation to their vegetative parts, therefore, act as natural cleaners (Gomes et al. 2014). These plant species include, *Eichhornia crassipes* (water hyacinth: WH), *Pistia stratiotes*, *Trapa natans*, *Typha domingensis*, *Phragmites australis*, etc. Such plants are highly adapted to hold hazardous HMs from water and transfer them to their vegetative tissues through the bioaccumulation process called “phytoremediation” (Rezania et al. 2016; Dubey and Dutta 2020). However, the HM bioaccumulation affinity of plants is largely associated with their genetic compatibility. Since the bioaccumulation of HMs is a natural process, it is widely used for the sustainable decontamination of various types of wastewaters (Kumar et al. 2019a). Besides this, the mechanism of plant growth and HM uptake is a complex process governed by several intrinsic and extrinsic factors (Eid et al. 2020). Therefore, plant growth and HMs mobility need to be investigated properly through an efficient process in a very large case study area.

Lakes and wetlands represent significant macrophyte growths and therefore a huge sink of nutrient-rich biomass (de la Varga et al. 2020). These growing plants create a pool between the sediment, water, and plant biomass by which the wetlands do nutrient recycling (Qasaimeh et al. 2015). However, if the nutrients’ accumulation in sediment is a cumulative process, the lake turns into a wetland and then a wetland, and then into a land. This turnover is harmful to both aquatic fauna and flora of lakes and wetlands. Thus, efficient strategies should be adopted to halt nutrient enrichment and clean the invasive species from water bodies regularly (Galal et al. 2018). Previous studies have used quadrat and geographical information systems to estimate the role of aquatic macrophytes biomass (Eid et al. 2010; Converse et al. 2015; Ofir et al. 2017; Kadam et al. 2017). Besides this, lake and wetland modeling based on distance and time-series data may provide better insight into the functioning of such systems. From the model simulated results, decisions could

be efficient regarding biomass harvesting and its utilization. Moreover, the developed models could be used to assess the potential of aquatic plants in the water body decontamination process.

Until recent date, no study has been carried out to investigate the WH growth and nutrients accumulation patterns in the un-operated old Ganga canal in Haridwar, India. Thus, this is the first study to investigate the annual WH growth and nutrients accumulation from the old Ganga canal system at Haridwar. The current study presented an effective method to measure the WH growth and nutrients accumulation patterns using prediction models. Keeping in view the findings of this study, immediate measures are suggested to prevent the disposal of HM-holding wastewater. This leads to extensive WH growth while the biomass should be harvested regularly and used for certain sustainable production purposes.

2 Materials and methods

2.1 Description of the study area

Ganges (Lat. 24° 38' to 48.0444" N and Long. 87° 47' to 30.2777" E) is one of the longest (2525 km) rivers of the Indian subcontinent. The river's system includes many perennial and non-perennial rivers that originate from the Himalayas (Jain et al. 2020). It starts from Uttarakhand, India, and ends up in the Bay of Bengal in the Indian Ocean. The river passes through five Indian states including, Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal. In the Indian state of Uttarakhand, Haridwar is the place where the river Ganges comes out in planes. From this point, Ganges has been divided into two connecting canal systems to provide irrigation water to the agricultural lands beneath the Himalayan planes (Jain and Tandon 2010). The three major states including Uttarakhand, Uttar Pradesh, and Bihar are mutually benefitted from the water of these irrigation canal systems. The upper Ganga canal system (UGCS) has its origin point at Haridwar which provides the irrigation water to the lands of the doab region between the Ganga and Yamuna rivers. It covers nearly 9575 km of combined length in total (IGI, 2020; WUPD 2014).

The old Ganga canal was constructed in 1850 under the administration of Proby T. Cautley during British rule in India. From Haridwar to the Roorkee cities of Uttarakhand state, there is an old and non-operational stretch of the upper Ganga canal having an average width of 100 m and a length of 25 km. It was declared non-suitable or abandoned for use after the construction of a new parallel canal in the late twentieth century (Figs. 1 and 2) (IGI, 2021). Although the old Ganga canal does not receive water from the new Ganga canal system, it still receives a huge volume

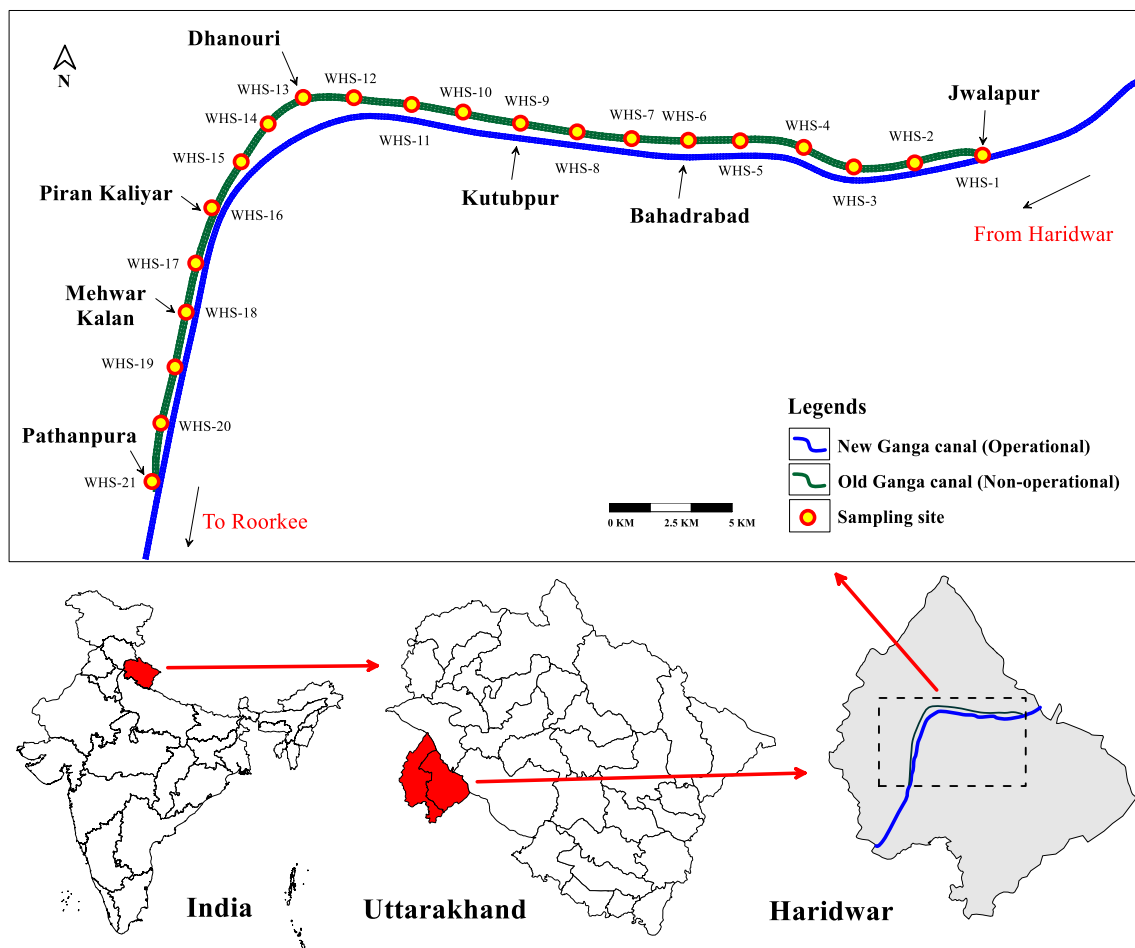


Fig. 1 Map view of the study area (old and new upper Ganga canal at Haridwar, India) with sampling sites



Fig. 2 View of the study sites; **a** New Ganga canal; **b** un-operated old Ganga canal with extensive water hyacinth growth

of agricultural runoff, rainwater, effluents from some manufacturing units, and wastewaters from nearby villages, towns, and mass tourism points (Table 1). Yearly, the un-operated old Ganga canal is dominated by extensive growth of water hyacinth (*Eichhornia crassipes*) as a result of nutrients mixing from nearby wastewater disposal points. Therefore, the un-operated old Ganga canal was selected for biomonitoring

of water hyacinth (WH) growth and heavy metals accumulation potentials.

2.2 Field methods

For the biomonitoring studies, standard protocols of field samplings were adopted. Since water hyacinth growth in the canal

Table 1 Description of sampling sites at the un-operated old Ganga canal (Geo-coordinates and elevation data obtained from Google Earth Pro; WGS84, Google)

Site name	Distance (km)	Coded name	Geo-coordinates	Elevation (m)	Remark
Jawalapur	0	WHS-1	29° 55' 09.9" N 78° 06' 06.8" E	280	Origin point
	1.25	WHS-2	29° 55' 08.6" N 78° 05' 20.7" E	280	Wastewater mixing from nearby villages and effluents of some manufacturing units of adjoining towns
	2.5	WHS-3	29° 55' 11.1" N 78° 04' 33.2" E	279	
	3.75	WHS-4	29° 55' 14.8" N 78° 03' 48.1" E	275	
Bahadrapad	5	WHS-5	29° 55' 22.7" N 78° 03' 02.6" E	274	
	6.25	WHS-6	29° 55' 39.1" N 78° 02' 22.7" E	273	
	7.5	WHS-7	29° 55' 38.9" N 78° 01' 37.0" E	272	
	8.75	WHS-8	29° 55' 48.4" N 78° 00' 51.6" E	272	
Kutubpur	10	WHS-9	29° 55' 58.0" N 78° 00' 06.2" E	271	
	11.25	WHS-10	29° 56' 06.7" N 77° 59' 20.9" E	271	
	12.5	WHS-11	29° 56' 14.8" N 77° 58' 43.1" E	270	
	13.75	WHS-12	29° 56' 24.8" N 77° 57' 50.3" E	270	
Dhanauri	15	WHS-13	29° 56' 22.6" N 77° 57' 07.0" E	269	Wastewater and runoff mixing
	16.25	WHS-14	29° 55' 46.3" N 77° 56' 32.1" E	269	
Piran Kaliyar	17.5	WHS-15	29° 55' 22.0" N 77° 56' 08.5" E	269	Municipal wastewater from mass tourism
	18.75	WHS-16	29° 54' 48.5" N 77° 55' 36.5" E	269	
Mehwar Kalan	20	WHS-17	29° 54' 20.9" N 77° 55' 08.8" E	267	
	21.25	WHS-18	29° 53' 50.1" N 77° 54' 38.4" E	267	
	22.5	WHS-19	29° 53' 50.1" N 77° 54' 38.4" E	267	
	23.75	WHS-20	29° 53' 25.7" N 77° 54' 15.1" E	267	
Pathanpura Roorkee	25	WHS-21	29° 52' 17.8" N 77° 53' 11.5" E	266	Endpoint and confluence point of old and new Ganga canal

starts in July and ends in December month, six months was considered for its biomonitoring. Purposely, the approximation of the old Ganga canal distance was done using the Google Earth Pro tool. The total numbers (n) of collective samples and collection points were 5 and 21, respectively (Table 1). Water hyacinth biomass was appraised at every 2.5 km distance by estimating the plant biomass in a 1×1 m quadrat. At the same point, water and plant biomass samples were collected in 200 mL PVC bottles and plastic bags, respectively. The composite samples from five quadrates were considered an effective point sample. The microbial growth in water samples was deactivated by the immediate addition of 3 drops of HNO_3 (concentrated).

2.3 Laboratory methods

Water and WH plant biomass samples were preserved at 4 °C before all laboratory analyses. For the estimation of heavy metals in WH, the biomass was oven-dried at 105 °C for 2 h followed by turning into a fine powder using a mechanical grinder. A total of 1 g sample was taken in 10 mL of double-distilled water and suspension was used for digestion. A di-acid mixture of a 3:1 ratio ($\text{H}_2\text{SO}_4:\text{HClO}_4$) was used as a digestate and extraction solution. Water and plant biomass samples were digested at 250 °C for 2 h and the final volume of the content was made to 50 mL by addition of 3% HNO_3 . Finally, heavy

metal contents were analyzed using atomic absorption spectroscopy (AAS, Analyst 800, PerkinElmer GenTech Scientific Inc., Arcade, NY) while setting the analyzing conditions as per the instrument manual. Standard Reference Materials (SRM) were used to standardize the calibration curve by following quality assurance guidelines. The detection limits of Cd, Cr, Cu, Fe, Mn, and Zn elements were 0.002, 0.006, 0.003, 0.006, 0.002, and 0.001 mg/L, respectively. All protocols were outlined by the methods of APHA (2012) and Kumar et al. (2019c).

2.4 Mathematical model and verification

Since the irregular WH growth and heavy metals distribution patterns were not possible to predict using the linear models, we developed a modified cubic model (Kumar et al. 2019b; Sun and Wang 2020). During the two-year study period, simulation of WH growth, heavy metals contents in water, and plant biomass were done using a polynomial cubic function. Distance (0–25 km) and time (182–365 Gregorian days) series data were used as indeterminate to model specific maximum biomass production (y : Kg/m^2) and heavy metals contents in water (mg/L) and plant biomass (mg/Kg), respectively. The form of the polynomial cubic model used in the interpolation of time and distance series data is given in Eq. 1.

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 \quad (1)$$

where y was the predicted response variable, and x was the distance and time-series data as km, mg/L, and mg/Kg units, respectively.

On the other hand, the developed models were further tested for their application in real-time data. Purposely, three different model verification equations including model efficiency (ME), normalized error (NE), and model normalizing bias (MNB) were adopted (Kumar et al. 2019c). The tools used for model verification were given in Eqs. 2–4.

$$ME = 1 - \left[\frac{\sum (y_{model} - y_{actual})^2}{\sum (y_{model} - C)^2} \right] \quad (2)$$

$$NE = \left(\frac{\sum |y_{model} - y_{actual}|}{y_{actual}} \right) / n \quad (3)$$

$$MNB = \frac{\sum (y_{model} - y_{actual})}{\sum y_{actual}} \quad (4)$$

where y_{model} and y_{actual} are the models predicted and manually estimated response variables having a C mean value over n number of observations, respectively.

2.5 Data analysis methods

The most commonly used empirical method of HMs absorption by plants is the bioaccumulation factor. The effectiveness of water hyacinth for HMs absorption from the old Ganga canal was determined based on the bioaccumulation factor at the point of average growth (Eq. 5). Besides this, HMs accumulation potentiality of WH was determined based on the Accumulation of Nutrient Element (ANE) method (Parzych et al. 2018; Kumar et al. 2019b), in which the average percent participation (X) of each heavy metal was estimated using the standard formula (Eqs. 6 and 7).

$$\text{Bioaccumulation factor} = \text{HM in plant (mg/Kg)} / \text{HM in water (mg/L)} \quad (5)$$

$$Y = \sum_{i=1}^i (Z : z) \quad (6)$$

$$P = [(Z : z) 100] \times 1/Y \quad (7)$$

where Y and Z represented the sum (mmol_c per unit) and concentration of heavy metal in water (mg/L) and WH plant sample (mg/Kg), and z was the ionic valency of the metal element, respectively.

Before subjecting data to the model, it was analyzed for normality distribution. The coefficient of variance (CV %) was also analyzed to minimize the model building errors and uncertainty. All values were the mean of five standard observations. Google Earth, Microsoft Excel 2013, Origin Pro (2020b), and SPSS 23.0 (IBM) software were used for the data analysis.

3 Results and discussion

3.1 Water hyacinth growth potential and models

In this regard, significant dominance was recorded for WH plant growth in two seasons. During the course of the study, it was observed that WH was capable to grow for six months per year starting from July (Gregorian day 182) and ending up in December (Gregorian day 365). Results showed that WH grows in the entire un-operated old Ganga canal. However, the density of WH plants varied along with the distance factor. For the temporal variations, there was a below-average density recorded in July. It reached a maximum during October month and again declined to December. The increasing order of growth potential was followed as July < December < August < September < November. The maximum recorded density of water hyacinth was 18.954 kg/m² at the Piran Kaliyar sampling site where mass tourism takes place. However, the origin and endpoints of the un-operated old Ganga canal had relatively low WH growth. Since there were different pollutant mixing points throughout the entire canal, the growth of WH was also altered accordingly as revealed from Fig. 3. On the other side, there was a significant monthly variation in the growth potential of WH. The biomass density classification as provided in Fig. 3 showed that except for July and December months, all selected months showed dense and extreme WH growth in the un-operated old Ganga canal. In this, October and November months showed the highest extremes (> 12 kg/m²) WH growth.

On the other hand, the developed model equations can

be precisely used for the distance and time-series WH growth predictions. The given plot (Fig. 3) showed good fitness in terms of predicted and measured WH biomass growth (y). Table 2 provided the equation coefficients, verification, and ANOVA results of the distance series models for WH growth. The models had the most precise distance series prediction results for September month. They were characterized by a high coefficient of determination (R^2), high model efficiency (ME), low normalized error

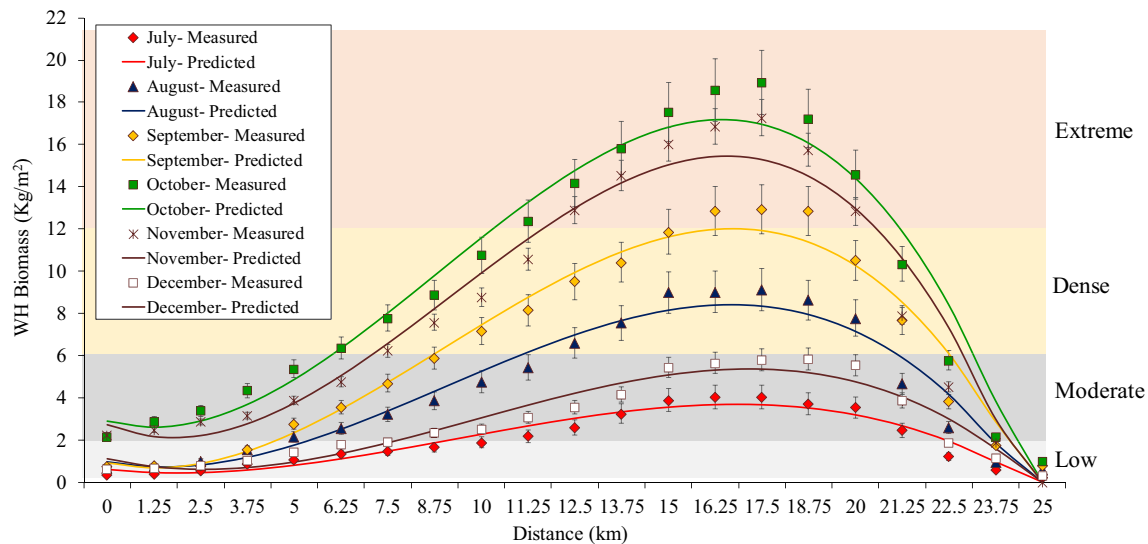


Fig. 3 Distance series measured vs. model predicted monthly water hyacinth biomass of un-operated old Ganga canal (Kg/m^2)

Table 2 Distance series models for predicting monthly water hyacinth biomass in un-operated old Ganga canal

Month	Model coefficients				Model validity				Model significance	
	β_0	β_i	β_i^2	β_i^3	R^2	ME	NE	MNB	F value	P value
July	0.594	-0.184	0.054	-0.001	0.93	0.99	0.02	0.01	76.19	<0.01
August	0.952	-0.329	0.119	-0.004	0.94	0.99	0.01	0.01	91.45	<0.01
September	0.905	-0.385	0.165	-0.006	0.95	0.99	0.01	0.01	134.42	<0.01
October	2.884	-0.490	0.218	-0.008	0.95	0.99	0.01	0.01	121.31	<0.01
November	2.710	-0.717	0.225	-0.008	0.93	0.99	0.02	0.01	87.53	<0.01
December	1.101	-0.408	0.090	-0.003	0.92	0.98	0.02	0.02	121.31	<0.01

(NE), and low mean normalized bias (MNB) as 0.92–0.95, 0.98–0.99, 0.01–0.02, and 0.01–0.2, respectively. ANOVA test of the adopted models showed a significant association of Prob (P) < F (confidence interval 0.99% or < 0.01) for their real-time applicability.

Previously, Eid et al. (2020) studied the annual potential of aquatic macrophytes, i.e., *Phragmites australis* during the eutrophication caused by nutrients accumulated in Lake Burullus, Egypt. They found that *P. australis* growth was associated with water and sediment nutrients properties of Lake Burullus. Another report by Shaltout et al. (2016) studied the phytomass dynamics of *Potamogeton crispus* L. in the water system Nile Delta, Egypt, and found that maximum growth was observed when the nutrients composition of lake water was the highest. Besides this, Sun and Zhu (2017) deliberated the application of remote sensing satellites for water hyacinth biomass growth for strategic harvesting. They found that using differential equation models makes it easy to predict large-scale WH growths. For instance, this study also showed that the polynomial cubic model can be used to predict WH growth in

the un-operated old Ganga canal which further may support decision-making in its harvesting.

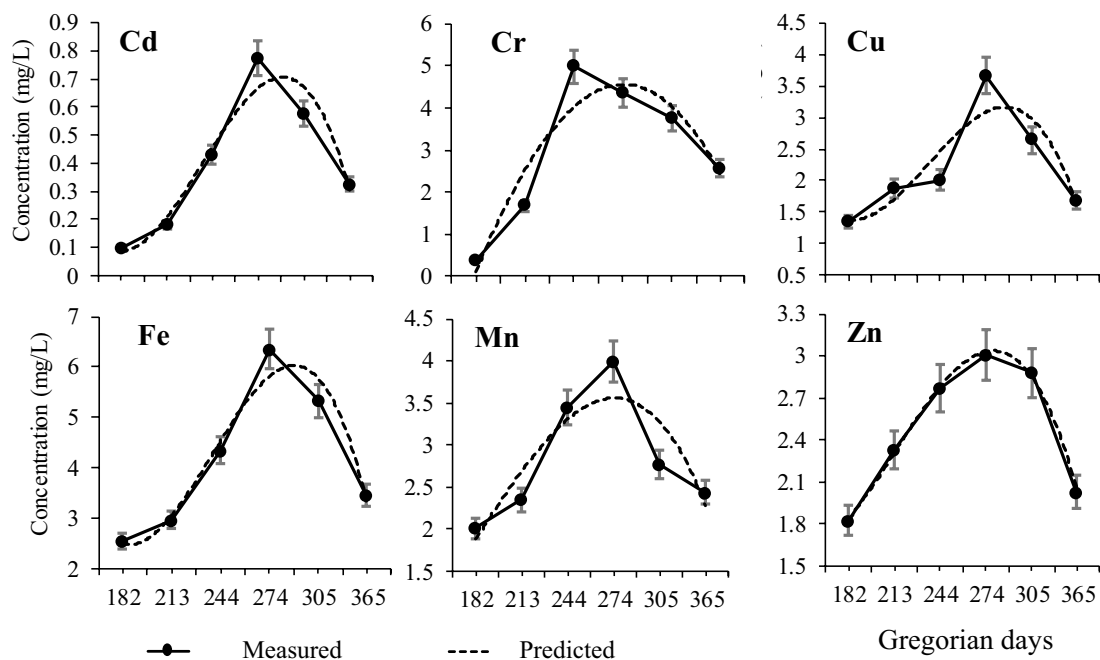
3.2 Heavy metals in old Ganga canal water

The heavy metals' data of un-operated old Ganga canal water indicated that their fraction increased from July to October and further decreased in December months, apparently. In this period, the peak concentration of all heavy metals was observed during September and October months. Table 3 showed the minimum, maximum, and mean HMs concentration in the water of the un-operated old Ganga canal. Also, the lowest HM load was observed in July which followed a cubic trend as given in Fig. 4. The highest contents (seasonal mean) of HMs including, Cd, Cr, Cu, Fe, Mn, and Zn, were 0.402, 2.951, 2.202, 4.170, 2.832, and 2.477 mg/L, respectively, for the two-year study period. Based on the seasonal average, the order of HMs in canal water was identified as $\text{Fe} > \text{Cr} > \text{Mn} > \text{Zn} > \text{Cu} > \text{Cd}$ based on their mg/L concentration. However, the CV of Cd showed the maximum fluctuations with the highest uncertainty which might be due to

Table 3 Minimum, maximum, and mean heavy metals concentration in the water and water hyacinth samples of un-operated old Ganga canal

Source	Heavy metal	Concentration			SD	CV (%)
		Minimum	Maximum	Mean		
Water sample (mg/L)	Cd	0.123	0.775	0.402	0.25	63.32
	Cr	0.356	4.355	2.951	1.75	59.32
	Cu	1.353	3.666	2.202	0.83	37.75
	Fe	2.550	6.360	4.170	1.46	35.14
	Mn	2.011	3.990	2.832	0.75	26.29
	Zn	1.827	3.010	2.477	0.49	19.60
Water hyacinth sample (mg/Kg dw)	Cd	0.166	2.880	1.503	1.01	67.28
	Cr	0.050	0.355	0.212	0.12	58.73
	Cu	0.981	2.983	2.192	0.80	36.33
	Fe	26.340	32.340	28.540	2.40	8.41
	Mn	19.342	23.242	20.791	1.40	6.74
	Zn	7.350	11.341	9.391	1.41	14.96

SD Standard deviation, CV Coefficient of variance

**Fig. 4** Mean heavy metals concentration in un-operated old Ganga canal water with measured and predicted ranges

the variations in the Cr load of wastewaters being disposed of in the canal from different sources as given in Table 1. Unlikely, Zn showed the least annual uncertainty as revealed from CV.

Table 4 provided the models for predicting the time-series HM load in the canal water. From the model fitting results, it was noted that the developed models had good fitness to predict temporal HMs load with acceptable R^2 ranging from 0.76 to 0.98, ME ranging from 0.93 to 0.99, NE from 0.01 to 0.03, and MNB from 0.01 to 0.04, respectively. All models had statistically significant $P < F$ values (0.01) that supported

the prediction confidence. On the other hand, based on the Accumulation of Nutrient Elements (ANE) results of canal water given in Table 6, the highest HM share was dominated by Fe (37.79%) followed by Cr (19.13%), Mn (17.41%), Zn (12.77%), Cu (11.70%), and Cd (1.19%), accordingly.

The findings of this work indicated that each year, the un-operated old Ganga canal is dominated by hazardous heavy metals which arise from the wastewater and runoff disposal from nearby villages, tourist places, agricultural files, and several manufacturing units. However, the heavy metals had a high temporal variability according to the WH growth. The

Table 4 Time-series models for predicting mean heavy metals concentration in water of un-operated old Ganga canal

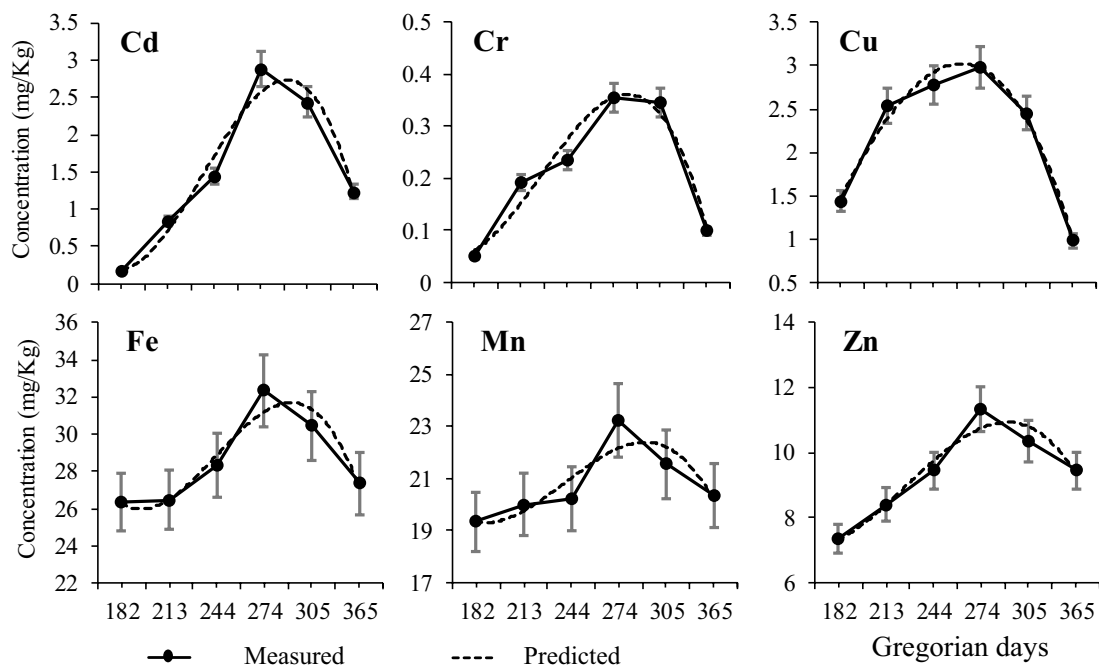
Heavy metal	Model coefficients				Model validity				Model significance	
	β_0	β_i	β_i^2	β_i^3	R^2	ME	NE	MNB	F value	P value
Cd	0.801	−1.397	0.891	−0.108	0.95	0.99	0.02	0.01	120.78	<0.01
Cr	0.076	−0.090	0.088	−0.012	0.94	0.99	0.01	0.01	117.66	<0.01
Cu	0.3853	1.153	−0.030	−0.024	0.98	0.99	0.01	0.01	167.21	<0.01
Fe	30.353	−6.965	3.241	−0.361	0.91	0.99	0.01	0.01	107.53	<0.01
Mn	20.84	−2.739	1.428	−0.165	0.76	0.93	0.03	0.04	40.35	<0.01
Zn	7.072	−0.373	0.718	−0.098	0.93	0.98	0.02	0.01	87.53	<0.01

wastewater disposal in the un-operated old Ganga canal is a cumulative process; therefore, water and sediment were dominated by hazardous HMs yearly. Previously, Dai et al. (2018) identified the sources of HM accumulation in Poyang Lake (China). They found that man-made practice was the most contributing factor for HM accumulation in its sediment fraction when analyzed using a multivariate geospatial model. Besides this, Rajeshkumar et al. (2018) also found significant seasonal HMs accumulation in the water and biotic community of Meiliang Bay (Taihu Lake, China) which arose from different wastewater disposal points.

3.3 Bioaccumulation of heavy metal by water hyacinth in old Ganga canal

Figure 5 showed a time-series variation in the HMs concentration in WH biomass of the canal. It was observed

that when plants started to grow in July, the HMs' load in their tissues was less which gradually increased exponentially up to October and further declined from November to December. Since October had maximum seasonal WH biomass growth, the HMs accumulation was also the highest. During the decline phase of the growth curve which was due to the aging and senescence of WH plants, the HM fraction in their tissues was also noted to be decreased. Table 3 provided the minimum, maximum, and mean HMs contents (mg/Kg dw) based on the analyzed dry WH biomass collected from the canal. Unlike HM loads in canal water, WH biomass showed different HM localization in their tissues. In this, Fe showed the maximum contents in whole plant tissues followed by Mn, Zn, Cu, Cd, and Cr, accordingly. However, maximum uncertainty was observed for the Cd in WH tissues followed by Cr, Cu, Zn, Fe, and Mn, respectively.

**Fig. 5** Mean heavy metals concentration in water hyacinth plant biomass with measured and predicted ranges

Moreover, the models predicting the time-series mean HMs concentration in WH plants were given in Table 5. The developed models having high R^2 (0.77–0.99), high ME (0.93–0.99), low NE (0.01–0.03), and low MNB (0.01–0.03) suggested that the equation can be effectively used to predict the mean seasonal HMs load of WH biomass in the canal. It was also reflected from the measured and predicted fitness curve given in Fig. 5. Since WH is adapted to accumulate most of the toxic heavy metals within its tissues, ANE analysis showed that based on the HM fraction (mmol_c/Kg) in WH biomass, Fe had the maximum share (57.19%) which indicated that Fe contents were utilized most efficiently and maximally from canal water (Table 6). Also, the bioaccumulation factor revealed the order of accumulation was noted as Mn > Fe > Zn > Cd > Cu > Cr which suggested a high affinity of Mn, Fe, and Zn uptake by WH.

Many reports showed that native macrophyte species have a high potential for nutrients recycling in the aquatic environment (Fawzy et al. 2012; Eid et al. 2019; Zare et al. 2020). Out of which, Fawzy et al. (2012) showed the phytoremediation capabilities of selected plant species growing in the Nile River of Egypt. Also, Eid et al. (2019) studied the potential of WH for HMs accumulation from the Nile Delta, Egypt. They found that a total of nine HMs were dominantly captured by the WH from the water of the Nile Delta, and concluded that it is acting as a natural river water cleaner. However, the potential uptake of WH was different

according to HMs toxicity. Similarly in another study, Eid et al. (2021) investigated the uptake of nine HMs uptake by water hyacinth grown in irrigated canals of the North Nile Delta. They found that the levels of heavy metals in water hyacinth tissues were significantly correlated with their concentration in canal water. A recent report by Zare et al. (2020) showed that the selected aquatic macrophytes (*Tamarix* sp., *Suada* sp., and *Juncus* sp.) were able to remove a significant fraction of HMs (Cd, Cr, Cu, Fe, Mn, Pb, and Zn) from Maharlu Lake (Fars province, Iran). They found a positive correlation between the HMs load in water and their removal efficiency by native plants. Thus, the above results showed that WH had a significant role in HMs recycling in the water of the un-operated old Ganga canal at Haridwar.

3.4 Water hyacinth biomass potentials

Table 7 provided the potentials of WH biomass grown in the un-operated old Ganga canal at Haridwar. Since the total un-operated stretch of the old Ganga canal showed high WH growth, it described that there are many sustainable management opportunities associated with its growth and biomass. The average annual WH biomass density in the un-operated old Ganga canal was 5.538 kg/m². Besides this, the average HMs' accumulation potentials of biomass WH were 1.50 mg/Kg dw for Cd, 0.21 for mg/Kg dw for Cr, 2.19 mg/Kg dw for Cu, 28.54 mg/Kg dw for Fe, 20.79 mg/

Table 5 Time-series models for predicting mean heavy metals concentration in water hyacinth plants of un-operated old Ganga canal

Heavy metal	Model coefficients				Model validity				Model significance	
	β_0	β_i	β_i^2	β_i^3	R^2	ME	NE	MNB	F value	P value
Cd	0.265	−0.384	0.233	−0.028	0.92	0.98	0.02	0.01	39.22	<0.01
Cr	−3.143	3.651	−0.387	−0.011	0.88	0.96	0.03	0.02	24.35	<0.01
Cu	2.034	−1.350	0.784	−0.095	0.79	0.94	0.03	0.03	19.45	<0.01
Fe	3.961	−2.848	1.568	−0.185	0.94	0.98	0.03	0.02	57.39	<0.01
Mn	1.042	0.801	0.0685	−0.027	0.77	0.93	0.04	0.03	17.24	<0.01
Zn	1.562	0.099	0.207	−0.035	0.99	0.99	0.01	0.01	126.17	<0.01

Table 6 Bioaccumulation factor and ANE results of heavy metals concentration in the water and water hyacinth samples of un-operated old Ganga canal

Heavy metal	Bioaccumulation factor	ANE			
		Canal water		Water hyacinth	
		Mean ± SD (mmol _c /L)	P (%)	Mean ± SD (mmol _c /Kg)	P (%)
∑ heavy metals	–	15.026 ± 1.233	100	62.622 ± 11.733	100
Cd	3.76	0.398	1.19	1.499	0.99
Cr	0.07	2.948	19.13	0.213	0.31
Cu	0.99	2.203	11.70	2.192	2.57
Fe	6.84	4.169	37.79	28.542	57.19
Mn	7.33	2.834	17.41	20.785	28.22
Zn	3.79	2.475	12.77	9.391	10.71

ANE Accumulation of Nutrient Elements, SD Standard deviation, P Percent participation

Table 7 Potentials reported for water hyacinth biomass for various purposes

Water hyacinth potential	Average value	Unit	Reference
Biomass production	5.538	Kg/m ² per annum	This study
Cd accumulation	1.50	mg/Kg dw. per annum	
Cr accumulation	0.21		
Cu accumulation	2.19		
Fe accumulation	28.54		
Mn accumulation	20.79		
Zn accumulation	9.39		
Cd accumulation	0.341	mg/Kg dw	Du et al. (2020)
Cr accumulation	60.8		
Cu accumulation	43.5		
Fe accumulation	–		
Mn accumulation	958		
Zn accumulation	197		
Bioethanol production	1.40	g/L dw	Zhang et al. (2018)
Biogas production	2708	mL/100 g dw	Kumar et al. (2018)
Bio-briquette production	17.17	MJ/kg calorific value	Rezania et al. (2016)
Biochar production potential	68	% yield dw. basis	El-Azeim (2021)

Kg dw for Mn, and 9.39 mg/Kg dw for Zn, respectively. These findings showed that the pollutants accumulated from nearby sources were effectively localized into the vegetative tissues of WH. Many previous studies have confirmed that the biomass of aquatic macrophytes from water bodies should be harvested when they achieve maximum growth. The biomass can be used for a variety of purposes in sustainable production including low-cost bioethanol, biogas, biodiesel, biochar, and briquette production (Rezania et al. 2015, 2016; Yan et al. 2017; Kumar et al. 2018; Zhang et al. 2018). This may serve as an alternative source of energy and industrial material. Although, to date, no practice of biomass harvesting is done in the un-operated old Ganga canal which needs special attention.

4 Conclusion

The present study concluded that the un-operated old Ganga canal showed a significant annual WH growth due to the addition of wastewater from nearby villages, tourist places, manufacturing units, and agricultural runoff. As a result of constant wastewater mixing, a huge load of HMs was reported in the water of the un-operated old Ganga canal. The polynomial cubic equation was helpful to construct high-quality models for distance and time-series prediction of WH biomass, HMs in water, and HMs in WH biomass, accordingly. The average annual WH biomass density in the un-operated old Ganga canal was 5.538 kg/m² with significant HMs accumulation. The regular WH biomass harvesting from the un-operated old Ganga canal may contribute to generating low-cost energy and industrial materials which

is highly recommended to the administration of Haridwar, India.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest/competing interests.

Ethics approval This article does not contain any studies with human participants or animals.

Consent to participate All authors mutually agreed to participate in this work.

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