Pollution,2(1): 25-34 , Winter 2016
DOI: 10.7508/pj.2016.01.003
Print ISSN 2383-451X Online ISSN: 2383-4501
Web Page: https://jpoll.ut.ac.ir Email: jpoll@ut.ac.ir

DO-BOD modeling of River Ganga from Devprayag to Roorkee, India using BMKB model

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Received: 10 Aug. 2015 Accepted: 4 Oct. 2015

ABSTRACT: The idea of systems analysis and mathematical modeling for formulating and resolving river pollution issues is of relatively recent vintage and has been applied widely in the last 3 decades. The present study illustrates the utility of Beck-modified Khanna–Bhutiani model (BMKB) to determine the pollution load due to the presence of organic matter in River Ganga from its course from Devprayag to Roorkee through the holy city of India, Haridwar. The study was conducted over a period of 3 years between 2010 and 2013. The study was aimed to verify the BMKB model for River Ganga. This model was simulated and calibrated through the data obtained by model by comparing it with the field data observed manually. Paired T-test were performed for dissolved oxygen (DO) and biochemical oxygen demand (BOD) between the titrated value and modelled value to determine if there was any statistically significant difference between the means of respective values. The results of T-test revealed statistically significant difference between DO and BOD, i.e., DO t (11)= 3.819, P= 0.003, BOD t(11)= 14.635, P= 0.000. The model presented with a good agreement between the calibrated and observed data, thereby actualizing the validity of the proposed model.

Keywords: biochemical oxygen demand, BMKB model, dissolved oxygen, mathematical modeling, River Ganga

INTRODUCTION

River Ganga, the holiest river of all rivers and the lifeline of north India originates from the Gangotri glaciers. It emerges as a result of the confluence of the main streams of two important hill rivers, river Bhagirathi and river Alaknanda, at Devprayag. From Hardwar, these river flows down south and then south-east via several important cities such as Garh Mukteshwar, Anupshahar, and Narora in Bulandshahar, the metro towns Kanpur, Allahabad, Varanasi, and finally terminating into the Bay of Bengal, covering a total of about 2,525 km during its course in India. The river Ganges is regarded as the most holy and sacred rivers of the world from time immemorial. It occupies a unique position in the ethos of Indians. The river's name in Hindi, the chief Indian language, is Ganga. It is regarded as the river from heavens and therefore has a special sentimental place among its worshipers.

It is well-known that Ganga is one of the most important rivers of India and has served as a cradle for Indian civilization. Although there are several large cities along the banks of Ganga river, where the river serves as the source of water. Over the years, the river has been indiscriminately polluted and misused (Pandey *et al*. 2014). Despite its extraordinary resilience and recuperative capacity, it has become severely polluted now. Due to the increase in the population and industrialization

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activities, the water quality of river Ganga has been damaged from the addition of domestic sewage and industrial effluents containing large numbers of chemicals and heavy metals. Waste materials react with each other, resulting in the pollution of the water, making it toxic; such a toxic water ultimately makes the water non-potable and severely affects the bio-productivity of the aquatic system. Singh and Choudhary (2013) studied the physico-chemical characteristics of the water of River Ganga in the middle of Ganga plains. Tripathi *et al*. (2014) studied the physico-chemical parameters and the correlation coefficient of the River Ganga at Shringverpur, Allahabad. In addition, various other aspects related to water quality of the River Ganga have been widely studied by different workers in the literature (Khanna and Bhutiani, 2003; Khanna and Bhutiani, 2005; Khanna *et al*. 2007; Khanna *et al*. 2011; Khanna *et al*. 2012; Khanna *et al*. 2013; Bhutiani *et al*. 2015; Bhutiani *et al*. 2015).

Methods based on the mathematical modeling provide an excellent method in controlling several limnological components. Thus, the analysis based on mathematical modeling will indeed serve as the backbone of the studied process. Mathematical modeling aims at defining the quantitatively alternative course of action. It provides a useful means for evaluating the pollution problem in an appropriate manner. Indeed, the idea of comprehensive analysis is not entirely new, rather it is an approach for the usage of better quality water, as witnessed and recognized in the recent years.

A framework that enables the study of, for example, the consequences of human influences on the ecological systems without disturbing these, is a valuable and important tool for environmental management. Models are therefore identified as important and necessary tools for the studying of and for understanding the ecological processes, for testing hypotheses of the functioning of ecosystems in a systematic manner, as well as for investigating the environmental response to human impact. This makes modeling an important part of the interdisciplinary research field of environmental science. However, ecological modeling is performed rarely by mathematicians, but extensively by practicing ecologists and environmental scientists.

The holy city of Haridwar is located in the north Indian state of Uttarakhand at a distance of 214 km from Delhi, at the foothills of Shivalik. Haridwar extends from the latitude 29°58' in the north to the longitude 78°13' in the east. The city is situated at a height of almost 300 m above the sea level, and has a temperature of around 40°C during summers. In winters, the temperature dips to as low as 6°C. Knowing the significance of dissolved oxygen (DO)–biochemical oxygen demand (BOD) interaction is extremely important to consider DO-BOD models based upon mathematical equation and few physical laws. Beck (1974) presented a detailed discussion of the processes governing DO–BOD interaction. Before him, Streeter and Phelps (1925) used mathematical models for BOD and DO for the first time. Several models have been suggested/developed and applied since then (Masch, 1970; Morley 1979; Orlob, 1983; Vogler and Scherfig, 2004).

The present study was undertaken to demonstrate changes in the water quality by considering the representative water quality characteristics of the River Ganga as well as the intended use of water. The use of mathematical models results in an increased capability for defining and evaluating possible alternatives as well as provides for a wider range of options at every level of decision-making. Our study used the recently developed BMKB model (2004) based upon the Beck model (1974) regarding DO and BOD to assess the extent of pollution in River Ganga.

MATERIALS AND METHODS

Study Sites

A total of 5 sampling sites (Fig. 1) were selected to verify the BMKB model in the River Ganga from Devprayag to Roorkee. The sites were selected, because, at Rishikesh, the turbulent velocity of River Ganga was high in comparison to that in Haridwar. This turbulent velocity played an important role in the BOD–DO interaction. Therefore, to evaluate the changes in the aeration coefficient, it is important to know the complexity of interactions occurring between Devprayag and Haridwar.

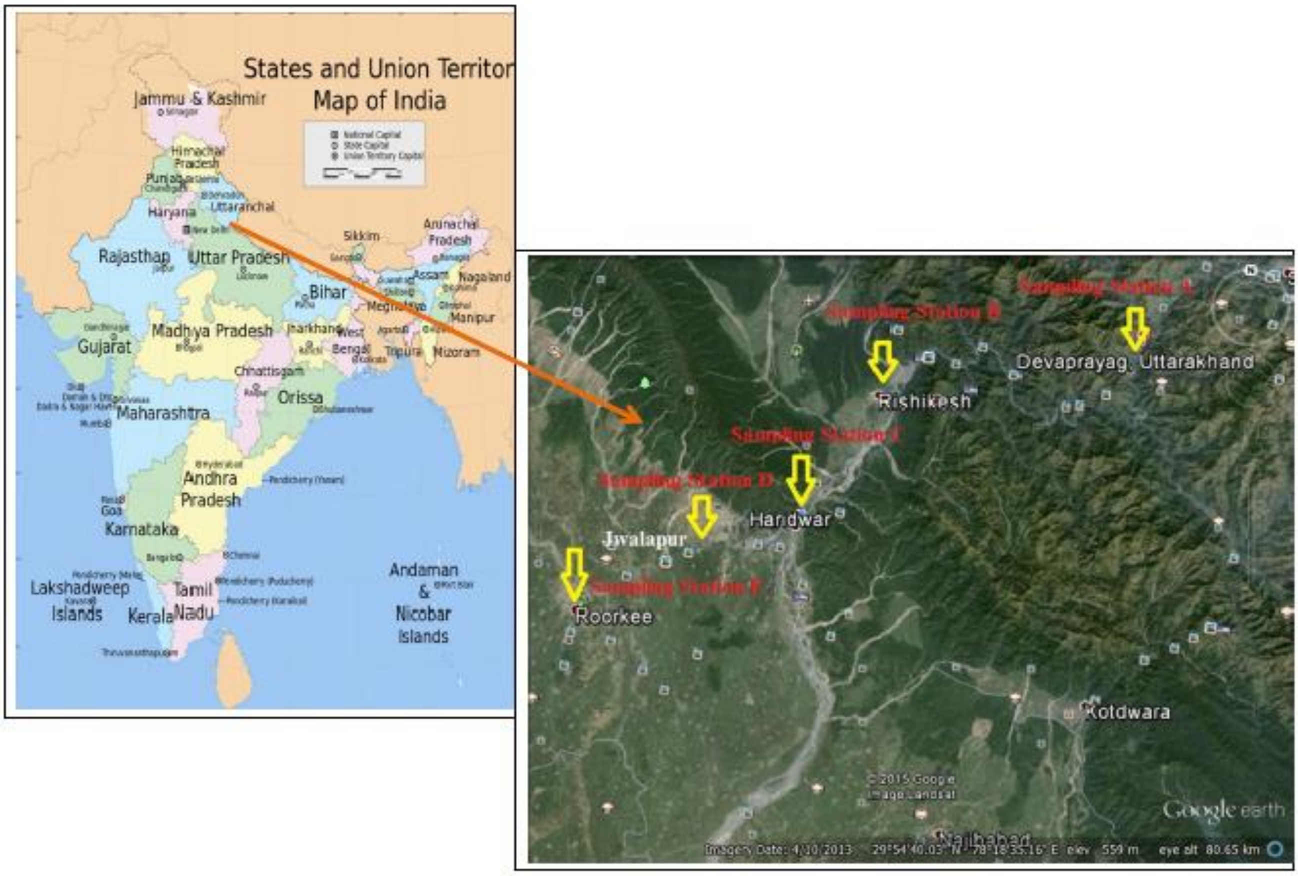


Fig. 1. Map showing sampling locations

Analysis for state variables

For the present study, water samples were collected in 300-ml BOD bottles on a monthly basis from different sampling stations, including (A) Devprayag, (B) Rishikesh, (C) Haridwar, (D) Jwalapur, and (E) Roorkee between 6:00 AM and 11:00 AM). Two state variables (DO and BOD) were analyzed on the spot and in laboratory for 36 months (2010–2013) as per the standards methods of APHA, 2012 (Trivedy and Goel, 1984; Khanna and Bhutiani, 2005).

In the present study, DO was measured by the Winkler's method, which is a technique that measures DO in the freshwater systems. DO serves as an indicator of the health of a water body, where higher DO concentrations can be correlated with high productivity and less pollution. A sufficient level of oxygen must be present in any aquatic ecosystem to support life and facilitate the natural behavior of the species. Oxygen exists in water in the dissolved stage at a level equal to its saturation concentration, which is mostly dependent on the temperature of the water body.

DO was determined immediately after sample collection (on the spot analysis) by using the Winkler iodometric method, in which the manganese sulfate reacts with an alkali (KOH) to form a white precipitate of manganese hydroxide, which in the presence of oxygen oxidizes to a brown-colored compound. In the presence of strong acid, medium manganic ions are reduced by iodine, which in turn gets converted into iodine equivalent to the original concentration of oxygen in the sample. The BOD test is based upon determination of DO in a sample. This test measures the molecular oxygen utilized during a specified incubation period for the biochemical degradation of organic matter (carbonaceous demand) and the oxygen used to oxidize inorganic material such as sulfides and ferrous ions. In the present study, BOD was measured by measuring the DO concentrations in a sample before and after the predetermined incubation period.

Model framework

The BMKB model is based on multiple inputs and single output (Beck, 1974). This model provides the seasonal value on the basis of previously recorded upstream and downstream observations/concentrations of DO and BOD. The model proposed by Beck (1974) uses light intensity, while the present model is applicable when the light intensity is very less or negligible, such as in the monsoon season or in cloudy days. It is impossible to have mathematical models that totally confirms the nature and problem arising in all types of physical situations. Indeed, no model of a real system is perfect: if it were, we might call it a “White box” model. The DO model has a good potential for control applications, in the first instance, it is a very simple model, and, in the second instance, it does not require any information on the BOD conditions in the reach, as also mentioned by Beck (1974).

The BMKB model is the modified form of an earlier developed BOD–DO model by Beck (1974). The two multiple input/single output models by Beck (1974) are as follows:

$$\mathrm{DO}: \mathrm{y}_1(\mathrm{k}) = 0.715\,\mathrm{y}_1(\mathrm{k}-1) + 0.174\,\mathrm{u}_1(\mathrm{k}-1) + 0.057\,\mathrm{u}_3(\mathrm{k}) + 0.044\,\mathrm{u}_3(\mathrm{k}-1) + 0.554\,\mathrm{n}_1(\mathrm{k})$$

$$\mathbf{BOD}: \mathbf{y}_2(\mathbf{k}) = 0.751\mathbf{y}_2(\mathbf{k}-1) + 0.102\,\mathbf{u}_2(\mathbf{k}-1) + 0.048\,\mathbf{u}_3(\mathbf{k}-2) + 0.060\,\mathbf{u}_3(\mathbf{k}-4) + 0.618\,\mathbf{n}_2(\mathbf{k}) - 0.313\mathbf{n}_2(\mathbf{k}-1)$$

where,

y_1, y_2 = downstream observation of DO and BOD respectively, i.e., y_1 (k, z_1), y_2 (k, z_1)

u_1, u_2 = upstream observation of DO and BOD respectively, i.e., u_1 (k, z_0), u_2 (k, z_0)

n_1, n_2 = stochastic noise sequences

u_3 (k) = an observation of the sunlight incident on the system during the k^{ith} day (h/day).

Using these governing processes, Bhutiani and Khanna (2004) developed the BMKB model (Beck-modified Khanna–Bhutiani Model), which is used to obtain input/output, relationships of BOD and DO upstream and downstream of a river system. The BMKB model is largely motivated by the case study of river CAM Beck (1974), encompassing the parameters λ_1, λ_2, U_1, and e_1.

Precisely, we used the following model to study DO and BOD concentrations in River Ganga:

$$DO: \lambda_1(S) = C_1\lambda_1(S-1) + C_2U_1(S-1) + C_3e_1(S)$$

$$BOD: \lambda_2(S) = C_4\lambda_1(S-1) + C_5U_1(S-1) + C_6e_1(S)$$

where,

λ_1 (S) = DO value (mg/l) obtained in a particular season

λ_2 (S) = BOD value (mg/l) obtained in a particular season

λ_1 (S-1) = DO/BOD observation of the same place in a previous season

U_1 (S-1) = DO/BOD observation of upstream in a previous season

e_1 (S) = f (SD), errors of possibility

C_1, C_2, C_3, C_4, C_5, and C_6 are constants with the following values:

C_1=0.715 C_4=0.751

C_2=0.174 C_5=0.102

C_3 =0.554 C_6=0.313

Details of these constants are available in Beck (1974).

We used the BMKB model to verify the concentration of BOD and DO of Ganga River from Devprayag to Roorkee by comparing the values obtained using the model with manually obtained values.

RESULTS AND DISCUSSION

Model verification of any system depends upon the experimental result, indicating the model output and its interrelationship with other variables present in that particular system. The analyzed results of BOD and DO were applied in the model. The values of BOD and DO obtained manually as well as through the model are presented in Tables 1 and 2.

Table 1. Values of dissolved oxygen and biochemical demand as obtained from the BMKB model

Year	Dissolved Oxygen (DO)				Biochemical oxygen demand (BOD)			
	Site B	Site C	Site D	Site E	Site B	Site C	Site D	Site E
2010-2011	8.32mg/l	8.55 mg/l	9.11 mg/l	7.96 mg/l	1.96 mg/l	2.21 mg/l	1.66 mg/l	1.80 mg/l
2011-2012	8.62 mg/l	8.29 mg/l	7.94 mg/l	7.40 mg/l	2.00 mg/l	1.98mg/l	1.66 mg/l	2.42 mg/l
2012-13	8.17mg/l	8.64 mg/l	9.75 mg/l	7.56 mg/l	1.92 mg/l	2.27 mg/l	1.66 mg/l	1.66 mg/l

Table 2. Values of dissolved oxygen and biochemical demand as obtained manually through titration

Year	Dissolved Oxygen (DO)				Biochemical oxygen demand (BOD)			
	Site B	Site C	Site D	Site E	Site B	Site C	Site D	Site E
2010-2011	7.95mg/l ±(0.55)	8.18 mg/l ± (0.43)	7.95mg/l ±(0.61)	6.72mg/l ±(0.83)	3.12mg/l± (0.64)	3.22mg/l± (0.23)	2.97mg/l± (0.14)	2.88mg/l± (0.27)
2011-2012	8.00 mg/l ± (1.26)	7.93 mg/l ± (0.38)	7.58 mg/l ± (0.54)	6.70mg/l ± (0.62)	2.92 mg/l ± (0.48)	3.27 mg/l ± (0.28)	2.76 mg/l ± (0.27)	2.76 mg/l ± (0.20)
2012-13	8.30 mg/l ± (0.56)	8.52 mg/l ± (0.51)	7.52 mg/l ± (0.46)	6.60 mg/l ± (0.35)	3.03mg/l ±(0.66)	3.45mg/l ±(0.16)	2.78mg/l ±(0.24)	2.83mg/l ±(0.19)

The figures in bracket refers to the standard deviation

Figures 1 and 2 show the DO and BOD profiles, both predicted and measured, for the verification of the BMKB model for Ganga River. Statistical results revealed a correlation between the titrated value and the modeled value, as R = 0.530, R^2 = 0.281, F(1,10) = 3.910, P< .0005 for DO and R= 0.469, R^2= 0.220, F (1,10)= 2.814, P < .0005 for BOD, which was found to be significant in both the cases of the regression model with the two values: DO(t)= 3.176+0.537 DO (m) and BOD(t)= 2.221+0.402 BOD (m).

Moreover, this paired T-test was performed for DO and BOD between the titrated value and modeled value to search for any statistically significant difference between the means of the respective values. The results of T-test revealed a statistically significant difference between DO and BOD values, i.e., DO t (11)= 3.819, P= 0.003, BOD t (11) = 14.635, P= 0.000.

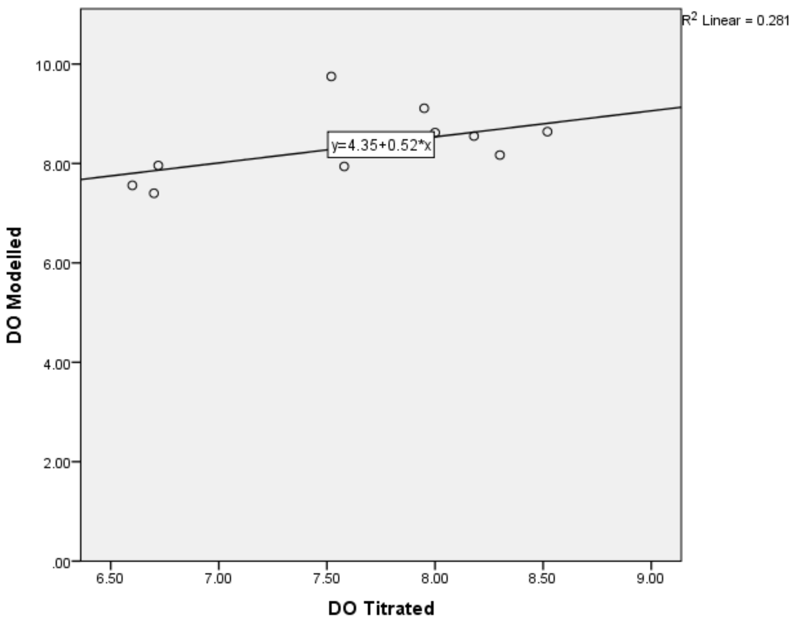


Fig. 1. The correlation between DO values as obtained by titration and by using the BMKB model

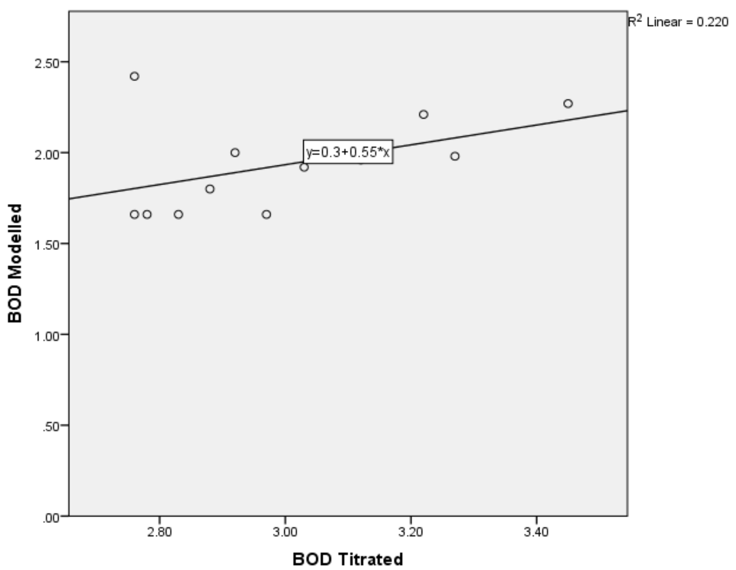
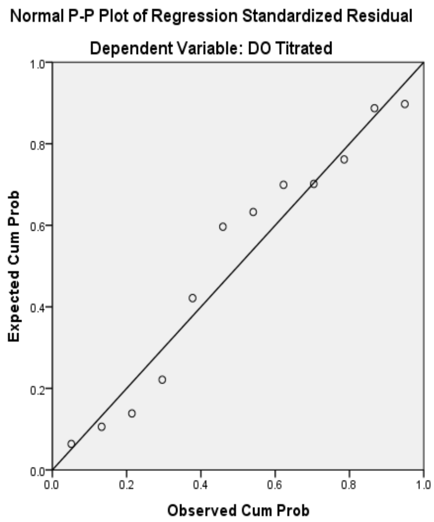
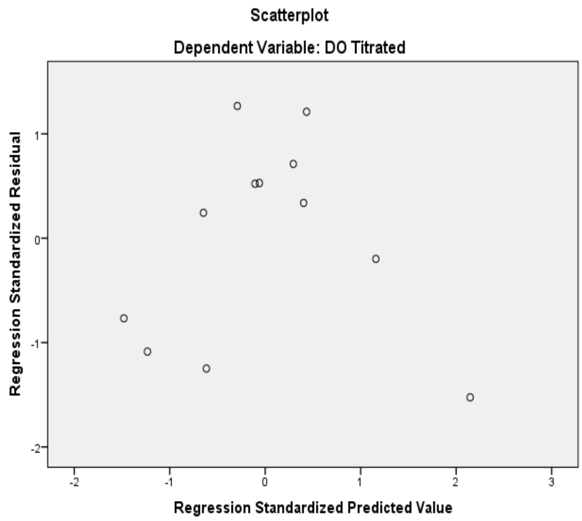


Fig. 2. The correlation between BOD values as obtained by titration and by using the BMKB model

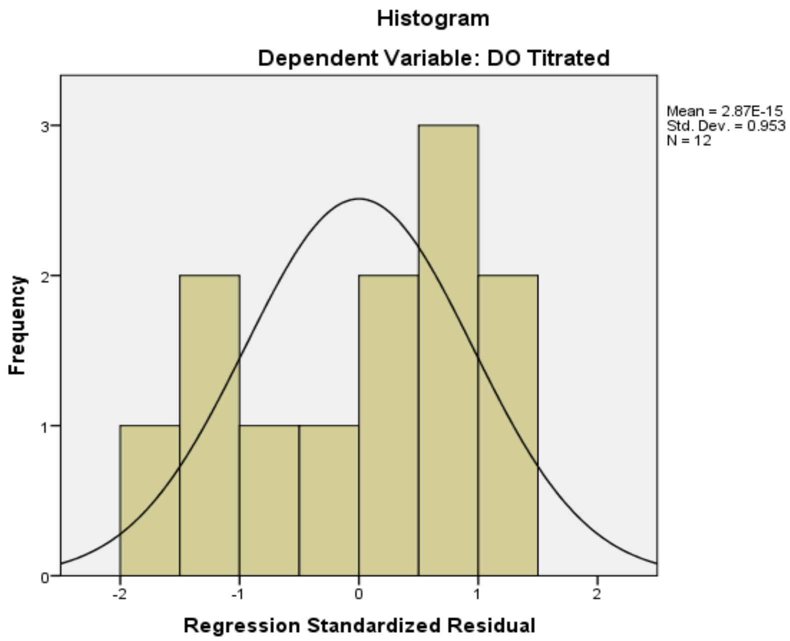
Figures 3 and 4 depict the error analyses of DO and BOD. It is evident from the histogram that the standardized residuals were approximately normally distributed in the both the cases. In both the figures, the regression plot of DO–BOD concentration showed 95% confidence level. The result showed that all the values were in 95% confidence band, thereby verifying the data accuracy.



a) Normal P-P plot showing normally distributed residuals

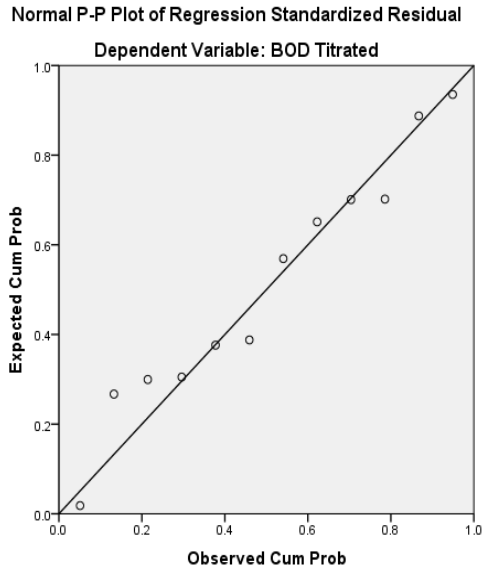


b) Scatter plot of standardized residual

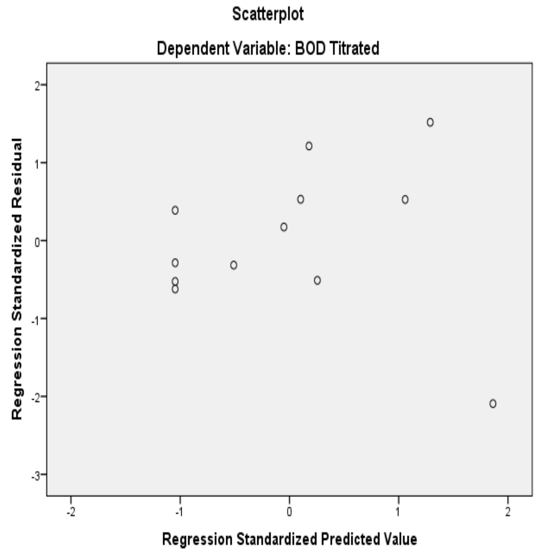


c) Histogram showing normally distributed standardized residual

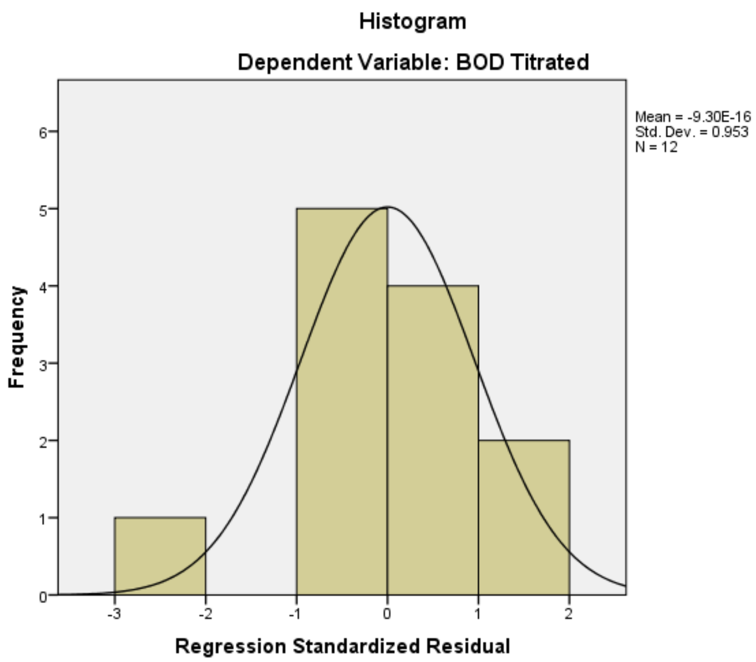
Fig. 3. Graph showing error analysis of DO



a) Normal P-P plot showing normally distributed residuals



b) Scatter plot of standardized residual



c) Histogram showing normally distributed standardized residu

Fig. 4. Graph showing error analysis of BOD

Mathematical modeling aims at defining the quantitatively alternative course of action. It provides a useful means for evaluating the pollution problem in an appropriate fashion. Indeed, the idea of comprehensive analysis is not entirely new, rather it is an approach for the usage of better quality water, as witnessed and recognized in the recent years. Various DO models have been developed based on the classical Streeter–Phelphs approach, including models incorporating oxygen demands by sediments and oxygen supply by photosynthesis as well as lake and reservoir models and models of surface water quality (Biswas, 1981; Grimsud *et al*. 1976; James, 1993).

In this paper, we presented the designs of input/output model (Beck model), and then represented each process of material input, interaction, and output by the proposed BMKB model, respectively, wherein the additional equations representing processes exploited the information of BOD and DO relation reactions. Finally, we showed that the 3-steps model offers the advantage of prediction and control by applying the numerical solutions model. Other parameters such as error analysis has little effect on the river DO over the range of variation, were the flow rate was tributary. BOD was also effected only slightly by the error analysis in our study. Various studies on the mathematical modeling of River Ganga has been done previously (Bhutiani and Khanna, 2007; Bhutiani and Khanna, 2009; Khanna *et al.* 2009; Khanna *et al.* 2009; Khanna *et al.* 2005). The result of using the proposed model was considerably in agreement with our findings at all the sampling sites of river Ganga, which is in concordance with the results obtained by Khanna *et al*. (2006) in river Suswa. An internally descriptive model exploited the available information on the phenomena determining the system's behaviors, e.g., the physical and biochemical mechanisms controlling the internal descriptions.

CONCLUSION

In this study, we investigated two water pollution models based on the BMKB model (the input/output model (or the Beck model). Our findings suggest that the BMKB model may be characterized as the "White Box model"; this model is the simplest model that can be used for any river system. This model uses multiple inputs with a single output, and both BOD and DO models have good potential for control applications. This paper presents the true verification and competition of the BMKB model with the experimental data. It seems that this modified model is a simplified once as compared to the Beck model (1974). Input and output results are quite accurate and the equation derivation with data is easier.

ACKNOWLEDGMENTS

The authors are thankful to the University Grant Commission New Delhi, India for providing financial support under major research project [file no.37-194/2009(SR)] for this study.

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