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Assessment of Chambal River Water Quality Parameters: A MATLAB Simulation Analysis

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Abstract: In this research work, environmental monitoring processes and assessments are carried out by the modeling and analysis of the water quality of the Chambal River in the state of Rajasthan. Various samples were collected from different locations along the course of the river flow. This water is used for different kinds of human, animal, and agriculture corp. activities. Comparative analyses were conducted on the water parameters, viz. biochemical oxygen demand, chemical oxygen demand, dissolved oxygen, total coliform, and conductivity, for the of consecutive years 2020 and 2021. A model was developed with the help of MATLAB Simulink software (Version R2019a) to find the causes of oxygen deficiency and reoxygenation in water with time and distance. The results of two consecutive years help to predict the responsible factors for the degradation of the river's water quality. The water quality modeling and simulation results conclude that the water quality of the Chambal River flowing through Rajasthan can rejuvenate itself during an alarming oxygen deficit within a short period. According to the results of this study, the concentration of dissolved oxygen in the water of the Chambal River is high enough to support the survival of the endangered species that inhabit the area.

Keywords: reoxygenation; deoxygenation; dissolved oxygen; oxygen deficit; biological oxygen demand; Streeter–Phelps equation

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1. Introduction

River water is an essential natural resource that may be used to support a variety of activities. This covers a variety of industrial activities within the river basin, as well as the generation of hydel energy, aquatic animal nutrition, drinking water, and other home purposes [1–3]. As a result, river water quality has a substantial impact on everyday human activities. This has motivated academics to assess river water quality in a variety of locations around the globe. Several similar river quality monitoring efforts have been recorded in the literature [4–6]. The testing of river water quality has become a standard procedure in most nations throughout the world.

Moreover, industrial activities proliferated by population growth within the river basins ought to enhance contamination of river water; therefore, degradation in river quality becomes a function of time and location. Again, the need for water projects interferes with the flow pattern of river water. There has been a notable difference in water quality between downstream and upstream. In a populous country like India, river water quality monitoring and the prediction of its possible degradation with time and distance are paramount. They cannot be postponed to any later date. Advanced modeling techniques connecting river water quality prediction over time and distance (from human intervention) are reported in the literature [7–9].

It is known that the Chambal is a very important river in Rajasthan concerning the sustenance of many endangered species. It is equally important for human activities within its basin. The Chambal River flows through the entire year, although its flow rate may vary from as high as 2074 cubic meters/second to a very low value of 58 cubic meters/second in the lean period [10–13]. The river provides the resources for developing cheap hydel power projects and ensures adequate irrigation facilities around the basin. Chambal is a unique river in India that accommodates the living of endangered species like gharial and river dolphins; moreover, it is the habitat place for the *magar machh*, black-necked storks, otters, whistling ducks, Indian skimmers, and freshwater turtles. Due to having four dams and many upcoming water projects, the flow of the river has diminished alarmingly by more than 40% within the last 50 years, and, as a result, it has suffered from the problem of oxygen deficiency; this tends to affect the population density of gharial, dolphins, and other aquatic species, which are found to be on the decline. The Chambal is the lone river in Rajasthan that organizes its landscape and determines the ecological setting of its basin. The Chambal River caters to the water needs of several cities situated on its banks. Besides being the major source of potable water, its importance in harboring rich biodiversity cannot be ignored [14,15]. However, the health of this river is greatly determined by the quality indices that sustain its richness and biodiversity. Being a tributary of the Yamuna River in Central India, it also constitutes a part of the Gangetic drainage system.

Being a legendary river, it is the most significant water resource of the state of Rajasthan in fulfilling the water demands of many cities and towns situated on its banks. A large part of the population, both in rural and urban sectors of Rajasthan, needs to depend on the Chambal River water to fulfill various livelihood requirements [16–18].

It is known that the average river health can be judged by its impact on human lives and the environment. The Chambal Basin is a populated river basin in Rajasthan that accommodates many people using the Chambal River's water for industrial, household, and other needful purposes. Thus, continuous water consumption, the introduction of many water projects, proliferating urbanization without regard to nature's wisdom, and reduced water flow create an ecological imbalance that finally impacts water quality. Huge water consumption for domestic, industrial, and agricultural purposes generates a huge amount of wastewater, the discharge of which without proper treatment will continue to affect the quality of river water. Similar experiences at different world locations are also reported in the literature [19–21]. Thus, one cannot ignore that water quality may degrade gradually, although it was hitherto described as a pollution-free river. It is, therefore, felt necessary to monitor the water quality of the portion of the Chambal River passing through the state of Rajasthan. This is why the present study is being conducted to understand the rate of water quality change so that remedial actions can be duly recommended. An attempt is also being made to model the oxygen deficit as a function of time and distance. Due to growing industrialization and uncontrolled urbanization, river pollution in the Chambal River has reached a critical stage, which is reduced oxygen in the water and water pollution that have negative impacts on all forms of aquatic life.

To assess the present water quality, a thorough analysis of selected quality parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total coliform, and conductivity is undertaken. Moreover, an attempt is made to predict the variation of deficient oxygen from simulation results of the BOD-DO relationship on the presumption that the Streeter–Phelps equation is valid for the present condition of the river. The main objective of the study is to obtain information on how much dissolved oxygen is present in the Chambal River's water, which is necessary for the survival of any endangered species that may be present there. MATLAB simulation modeling is used to simulate the water quality modeling in the Chambal River flowing through Rajasthan. The areas selected for the study are shown in Table 1.

Table 1. Comparative statement of water quality monitoring stations of Chambal River in Rajasthan.

Location	Name of Location/Station Identifier	Biochemical Oxygen Demand (mg/L)		Chemical Oxygen Demand (mg/L)		Dissolved Oxygen (mg/L)		Total Coliforms (MNP/100 mL)		Conductivity (µmho/cm)	
		2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Case-1	River Chambal entering in Rajasthan at Gandhi Sagar Dam	1.24	1.51	28.80	16.20	4.84	5.72	28	75	380	270
Case-2	River Chambal Akelgarh Kota U/S Kota Barrage at intake point of PHED	1.65	1.51	20.85	9.60	5.36	6.37	7	20	300	280
Case-3	River Chambal at Rangpur, Kota D/S (2 km from city)	2.47	3.13	30.86	33.60	3.91	3.78	120	210	670	610
Case-4	River Chambal at Keshoraipatan up-Stream near Raj Rajeshwar Mahadev Temple, district Bundi	2.37	3.24	39.20	36.40	4.64	3.35	75	210	690	620
Case-5	River Chambal at Keshoraipatan down-Stream near Ambedkar Nagar, district Bundi	5.56	4.32	70.89	41.20	3.09	2.59	210	210	730	640
Case-6	River Chambal at Rameshwar Ghat near Sawai Madhopur	1.85	2.70	18.86	23.40	4.32	4.10	75	120	640	570
Case-7	River Chambal near Chambal bridge Dholpur to Murena Road NH-3	2.06	2.81	13.94	29.88	5.87	4.64	28	150	670	600

2. Analysis of River Water's Quality Parameters

Seven locations were chosen to measure the water quality of the Chambal River. In all these locations, samples were collected simultaneously [10 a.m.] on the same day in April 2020 and April 2021. The sites were arbitrarily chosen to get an overall knowledge of water quality along the length of the river flowing through Rajasthan (shown in Figure 1), so the main sampling sites were not deliberately chosen.

Standard procedures laid down were employed to conduct water samples analyses [4]. In the present study, the quality parameters, viz. BOD in mg/L COD in mg/L, DO in mg/L, total coliforms (MPN/L), and conductivity (µmho/cm), were analyzed for all the sampling centers. Polypropylene bottles of 1 L capacity were used for collecting the samples. The bottles were washed with dilute acids.

One-liter polypropylene bottles were used for water quality parameter analysis, and 1 L glass bottles were used for pesticide analysis. Before sample collection, all bottles were washed with dilute acid, following which distilled water was used to clean the bottles. Finally, the bottles were rinsed thrice with the river water (whose analysis is to be carried out) and then dried in the oven. The bottles were duly marked for identification before collecting the test samples. The sampled bottles were preserved in the refrigerator until the samples were tested as prescribed.

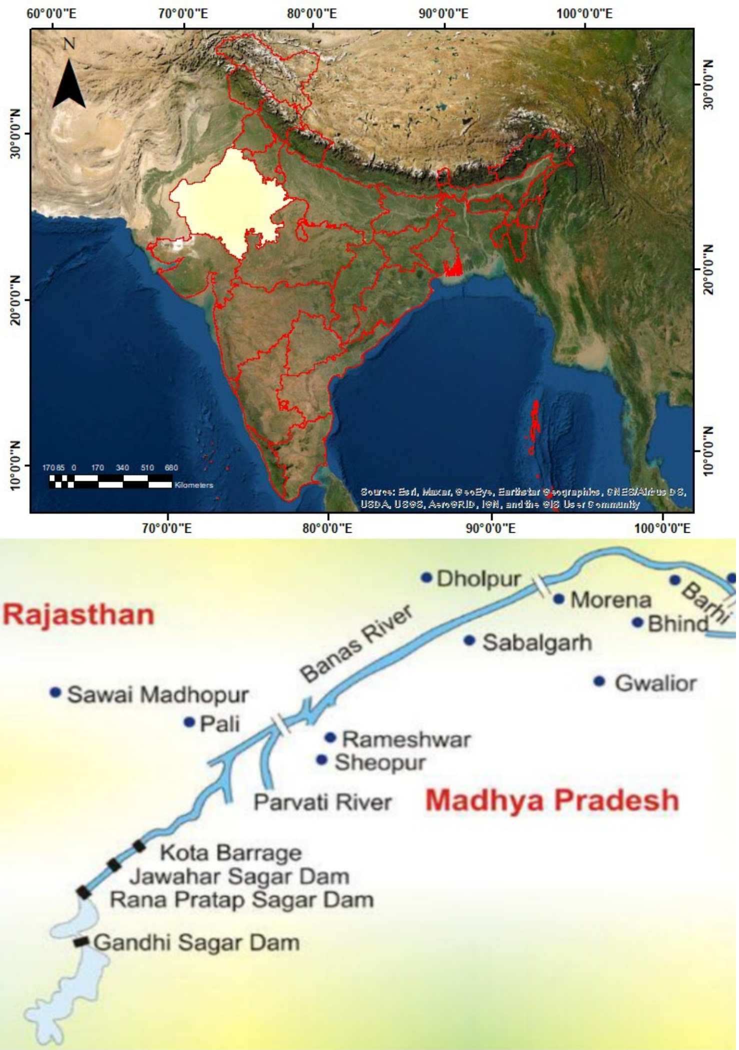


Figure 1. Study area map of Chambal River.

One of the most crucial indicators of the water quality in streams, rivers, and lakes is dissolved oxygen, or DO. It is a crucial evaluation of water pollution. The greater the water quality, the higher the dissolved oxygen concentration. Oxygen is particularly temperature-sensitive and only slightly soluble in water. Most trout populations, as well as populations of oxygen-sensitive aquatic insects like stoneflies, suffer when DO levels drop below 8 or 9. Trout and many other species of healthy aquatic life cannot survive in water with dissolved oxygen concentrations below 6 mg/L.

The daily variations of other parameters, such as temperature but also pH, can affect dissolved oxygen levels. This is brought up to show how water quality monitoring field data are simply snapshots in time (i.e., they only represent the quality or condition of the water at the time they were sampled). Because of this, monitoring the quality of the water must be done consistently throughout the year.

3. Methodology of Investigation

The Chambal River's water quality was evaluated at seven different sites. At the same time on the same day in April 2020 and April 2021, samples were taken from each of these locations. The primary sampling sites were not purposefully selected; rather, they were selected at random to provide a comprehensive understanding of water quality along the whole length of the river flowing through Rajasthan. It is common knowledge that the dissolved oxygen (DO) in river water is necessary not only for the survival of aquatic animals, but also for human consumption and other uses. In many parts of the world, rivers provide the primary supply of drinking water. However, the dissolved oxygen content of river water decreases as the river flows because biological organisms eat up a lot of DO while decomposing organic stuff in water and because some DO is used up for the unwelcome chemical oxidation of water. Therefore, unless oxygen is added, the dissolved oxygen content will continue to fall. The river constantly consumes the air's oxygen. Thus, the water in the river is subjected to two opposing forces. Deoxygenation is caused by the biological oxygen demand (BOD), while reaeration is brought about by oxygen absorption from the air. Environment management strategies can benefit from oxygen-deficiency prediction with distance and time to help reduce the degradation of river water quality. The mathematical model of oxygen deficit has been simulated in the MATLAB-Simulink environment, allowing for the prediction of the inevitable decrease in water quality with time or flowing distance. The simulation lasts for 25 days and can be run at any location along the Chambal River in Rajasthan. When the water leaves Rajasthan, it travels over 435 km to get to the next state. The aforementioned simulation work yields a forecast, which is subsequently tested using data from 2021, covering a time span four times larger than that utilized in the original experiment. This is carried out to prove the reliability of the forecasts made by the hypothetical mathematical model simulation. The methodology of the experiments is shown in Figure 2.

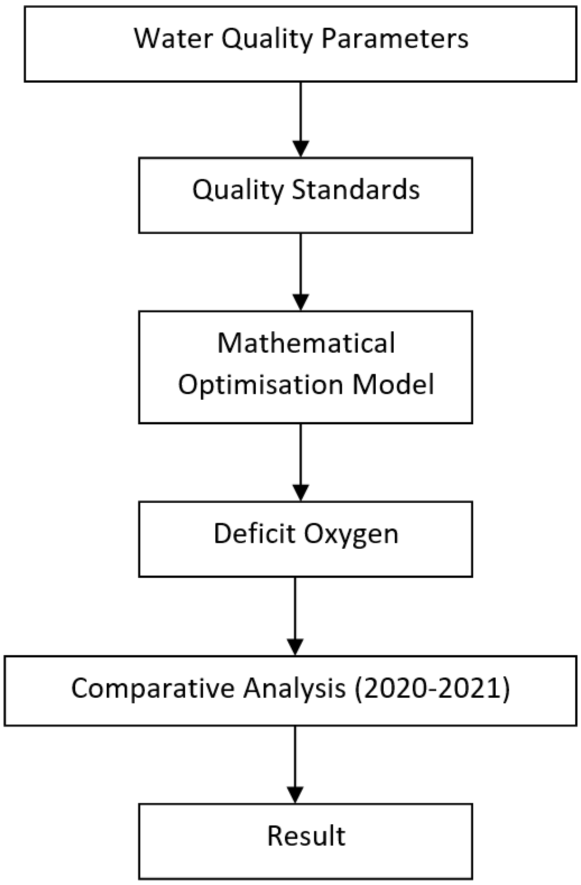


Figure 2. Experimental methodology.

4. Results

It is known that for the safe sustenance of aquatic lives, the dissolved oxygen content in a river must lie above 4 mg/L. In contrast, the minimum threshold value of DO in water for drinking purposes happens to be 6 mg/L. From the test results of Chambal River water (Table 1), it appears that the DO content in April 2020 has varied from 3.09 to 5.87 mg/L. It is evident that several comfortable areas ensure the comfortable living of aquatic animals in the Chambal River; however, some locations are found to be of concern because the DO content lies below the minimum threshold value. Again, the DO content along the river course under examination is generally unsuitable for drinking purposes unless suitable water purification treatment is carried out. Looking at the figures of DO content in 2021, it is seen that the values range from 2.39 to 6.37 mg/L. Suppose the results are compared with those reported by early workers [5–7]. In that case, one will notice that the value of DO as measured in the present study for the same location (Kota) corroborates that of the earlier study. Noticeably, the BOD content is alarmingly high compared to the requirement for drinking purposes, which is supposedly 0.2 mg/L. In the entire stretch of the Chambal River through Rajasthan, the BOD ranges from 1–2 mg/L except for at Ambedkar Nagar in the Bundi district. Thus, elaborate purification technology needs to be invoked to make this river water suitable for drinking. Again, the measured COD values are quite high against the stipulated standard of 4 mg/L for drinking purposes. Such a high value of COD in the Chambal River is indicative of the presence of a high concentration of organic and inorganic compounds that are chemically oxidizable. The lower amount of dissolved oxygen than expected is ascribed to the observed high value of COD.

Table 2 shows the statistical information of the water quality parameters of the Chambal River measured at various locations, as shown in Table 1. The variability or scatteredness in quality parameter values at several sampling locations can be seen in Table 2. This is particularly important for trend analysis in various quality parameters that are due to human intervention in different beneficial or detrimental manners. In the case of BOD, the dispersion is reasonable because its impact on the dissolved oxygen will not be too high over time or distance. It is also clear that the condition in 2021 was better regarding the scatteredness in the measured values. This is certainly a reflection of the maximum and minimum values obtained along the river course. So far as the oxidation of biological species goes, consistency among different locations on the stretch of the river in Rajasthan can be noted. In the case of COD, dispersion was alarmingly high in 2020 as marked by the high value of variance and, hence, standard deviation. This is apparently due to the high magnitude of difference in the maximum and minimum values of COD within the testing sites. This implies that there is a certain region that supplies a large amount of contaminants. From Table 1, it is clear that sample site five exhibits an exorbitantly high value of COD. Incidentally, that is the place, downstream Keshoraipatan, that is known to be infested by a large number of industries. Discharge of industrial waste may be a possible reason for the same. The dispersion in COD value lessened in 2021, as evidenced by a lower standard deviation of 10.51. Again, the maximum value was recorded at the same sample point. This is the location that creates the maximum contamination of the Chambal River water. Seemingly, better control steps were taken to curb the uncontrolled disposal of waste without treatment. It is clear that the lowering variance standard deviation and mean value in 2021 compared to 2020 has yielded a definite benefit in water quality when measured by the dissolved oxygen, the most important quality parameter determining the sustainability of aquatic lives and human beings. A lowering of dispersion reflects the benefit. Table 2 shows that the corresponding values of dissolved oxygen maintain the inverse relationship. A lower oxygen consumption agent in water ensures a higher amount of dissolved oxygen. It is also noted that the change in the dispersion of total coliform or conductivity remains almost the same in 2020 and 2021 when scaled against the absolute value at any place.

Table 2. Statistical analysis of water quality parameters of Chambal River.

	BOD		COD		DO		Total Coliform		Conductivity	
Year	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
Mean	2.45	2.74	31.91	27.18	4.57	4.36	77.57	142.14	582.85	512.85
Standard Deviation	1.32	0.91	17.72	10.51	0.85	1.22	64.64	69.48	157.10	151.72
Variance	1.75	0.84	314.12	110.57	0.75	1.50	4177.96	4827.55	24,677.55	23,020.41
Max. value	5.56	4.32	70.89	41.20	5.87	6.37	210	210	730	670
Min. Value	1.24	1.51	13.94	9.60	3.09	2.59	7	20	300	270

The nature of variations of water quality parameters along the river course from Gandhi Sagar Dam through to Dholpur's Chambal Bridge is shown in Figure 3a–e. Figure 3a shows the variation of BOD and the different sampling sites; it is apparent that the BOD content is generally on the rise until the fifth sampling site, downstream Keshoraipatan. At this point, maximum BOD is obtained, whereas, beyond this, the magnitude of BOD reduces; this means that the amount of organic matter becomes less concentrated beyond this point. The trend of maximum BOD at the above moment appears to be generic, as it was the highest BOD value in this site and it was also observed in 2021. Downstream, the observed lowering of BOD indicates river water contamination by the untreated domestic waste. Likewise, the industrial effluents contaminate water with more prevalent inorganic substances and raise the COD values. The trend of COD follows that of the BOD, and it is once again noticed in Figure 3b that the maximum COD was reached at downstream Keshoraipatan. This means that water quality at this location is extremely poor and is of great concern. The data of BOD and COD are found to be relatively good for the upstream areas. The high BOD and COD in the downstream compared to upstream values may be due to too much upstream withdrawal of water at site 2 at Akelgarh Kota U/S Kota Barrage, which reduces the dilution capacity of the river downstream, thereby degrading the water quality downstream at the site 5. Dissolved oxygen is a very important water quality parameter as it primarily determines the sustainability of aquatic lives.

Figure 3c shows the variation of dissolved oxygen (DO) content at the chosen locations along the river course. The DO test results show that the maximum available DO is available for site 2, whereas the minimum is found at site 5. Thus, the results of BOD, COD, and DO (Figure 3a–c) make it clear that the water quality varies with location and it becomes more polluted as the river progresses through Rajasthan. It is important to note that the water quality drastically degrades as a change from upstream to downstream takes place. Contrary to the general expectation, DO declines more downstream than upstream. This is possible only if more microorganisms remain to act for the biodegradation of organic matter by getting in contact with good quality river water. The results of the present investigation show that the behavioral pattern of variation in water quality was similar for both 2020 and 2021. This implies that the observations are consistent and, hence, phenomenological. Thus, in the concerned locations, human activities are probably responsible for adversely affecting the river water quality.

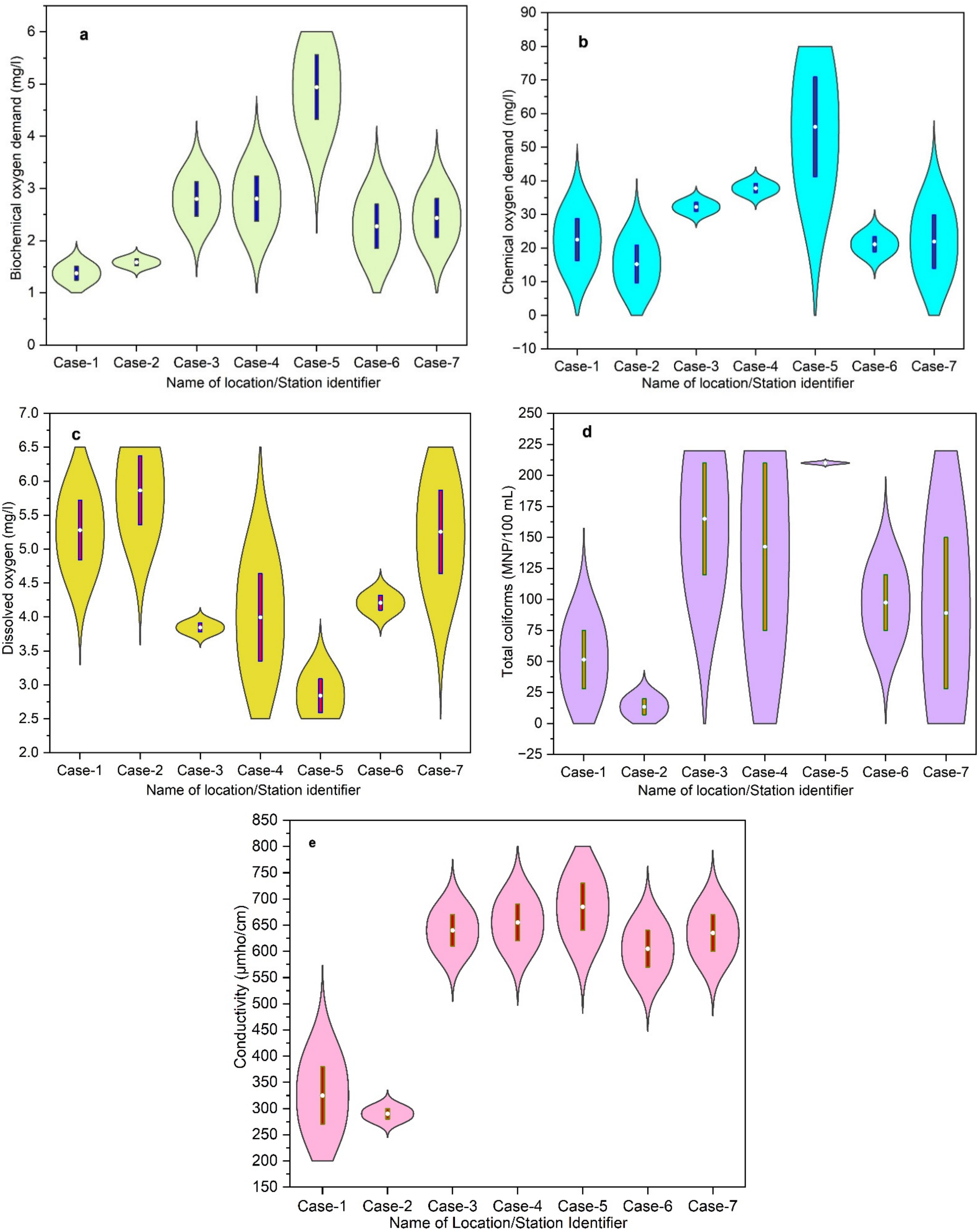


Figure 3. Violin graph for water quality monitoring stations of the Chambal River in Rajasthan: (**a**) biomedical oxygen demand, (**b**) chemical oxygen demand, (**c**) dissolved oxygen, (**d**) total coliforms, and (**e**) conductivity.

Figure 3d shows that except for at Akelgarh Kota U/S, the total coliform content is rather high in most of the places. This increased, entire coliform content is indicative of the possible presence of pathogens; these are supposed to owe their origin to the unplanned use of chemical fertilizers and the discharge of other industrial wastes. The maximum concentration of total coliform occurs at the region of downstream Keshoraipatan where the COD is also maximum; such an observation is attributed to the disposal of wastes generated in plenty by the considerable number of agro-based food-related industries situated around the location. Thus, large-scale industrial wastes, chemical fertilizers in agricultural activities, and other human wastes have led to such a high concentration of total coliform. Moreover, it is apparent from Figure 3e that the conductivity of Chambal River water flowing through Rajasthan ranges between 300–730 µmho/cm. The conductivity is found to be rather high in the downstream region. This observation agrees with the statement on Surma River water in Bangladesh (Alam et al. 2007). However, the conductivity range of Chambal River water lies within the safe limit for use for irrigation and drinking. The conductivity is normally influenced by the number of dissolved ions, types of ions present, and temperature. The water samples were taken in April 2020 and 2021; April is among the hotter months of Rajasthan, and its temperature shoots up to 48 °C within a range of 35 °C–48 °C. This is one of the reasons for the relatively high conductivity of Chambal River water in Rajasthan.

The sampling points were randomly chosen to get an overall picture of Chambal River water flowing through Rajasthan. While the analysis of water quality and probable reasons are discussed in the preceding paragraphs, the variation of water quality with the distance, measured from the first sampling point near the entry of the Chambal River into Rajasthan, viz. the Gandhi Sagar Dam, to the last sampling point at Dholpur where the river exits the state of Rajasthan is also mapped, and the results are furnished in Figure 4.

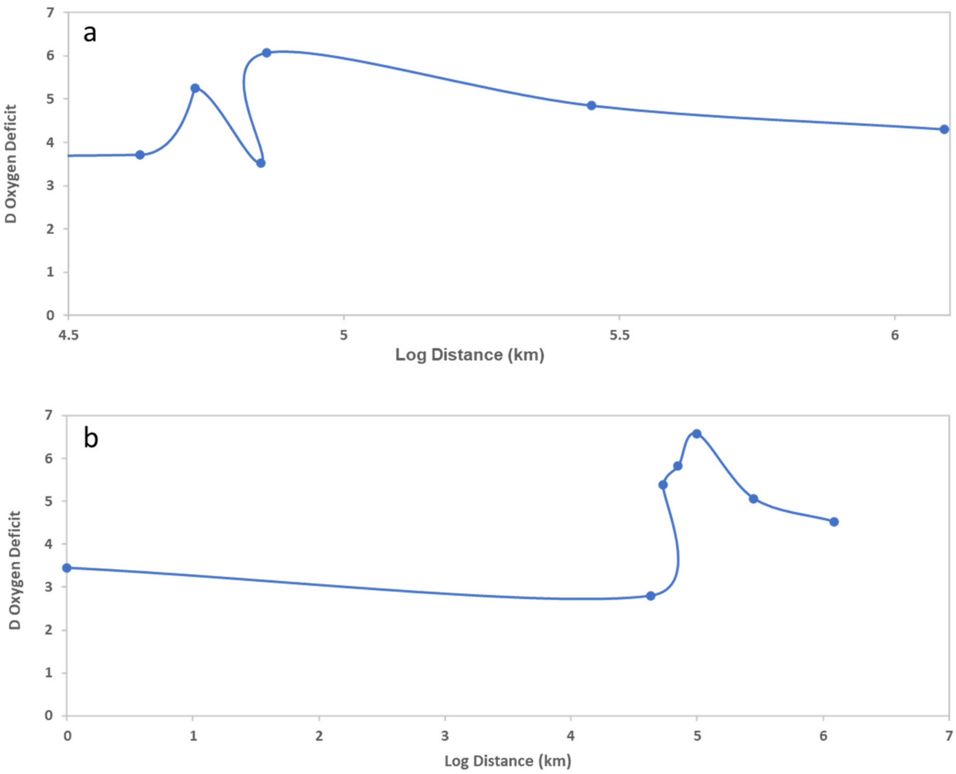


Figure 4. Variation of oxygen deficit with distance: (**a**) for the year 2020, (**b**) for the year 2021.

It is understood that the available oxygen in water is the fundamental factor in measuring water quality. The oxygen deficit against the saturation value of oxygen at the prevailing temperature is a good index to describe the quality of water so far as the sustenance of aquatic lives is concerned. Although other parameters are required to specify the overall quality of water, knowledge of oxygen deficit with time and, hence, the distance is of paramount importance to determine and recommend the necessary corrective steps.

Figure 4a shows the actual variation of oxygen deficit for the year 2020 (the difference between the saturation value of dissolved oxygen and the real value of DO at a certain time and location) as a function of the natural logarithm of distance. Following an initial decrease, the curve shows that a peak value of dissolved oxygen content is achieved as the river flows through Rajasthan after it enters Rajasthan. After attaining the peak value, the dissolved oxygen content gradually decreases and the curve becomes flattened at the later stages until it leaves the state of Rajasthan. Nearly similar observations can be made for the case of the year 2021. Thus, a consistency in the eventuality of influencing the water quality of the Chambal River is noted over the time. The minima of the curves in Figure 4a,b are seen to occur at the same distance from the entry point. This implies that some unique causes are responsible for such a decline in water quality. Relating the distance to the geographical location and the demography, it is observed that the region of lowest dissolved oxygen is a region highly vulnerable to experiencing contamination from various sources.

It is observed from the results of this study that the water quality parameters vary in a discontinuous manner within the portion of the Chambal River that flows through the state of Rajasthan. Hence, such an irregular pattern in the variation of oxygen deficit with distance can be also noticed. It is also observed that the water quality goes down appreciably in the downstream Keshoraipatan region. There are many instances of similar results in the case of a river flowing for a long stretch through any state or country. The parameters determining the water quality are greatly determined by the different types of proliferating human activities, including industrial agricultural and other domestic activities. With the increase in population density, a location-wise imbalance in different activities may be created, contaminating river water differently in various regions. While higher values of COD at specific locations signify a higher degree of pollution in river water that is due to the undesirable discharge of chemically oxidizable inorganic substances into the flowing stream, the concurrent rise in BOD indicates that the river water gets polluted with more organic matter being made to mix with it. The curves in Figure 4a,b delineate that organic wastes moderately contaminate Chambal River water at certain locations.

4.1. Deoxygenation Modeling

It is known that the oxygen dissolved (DO) in river water is required for the survival of aquatic animals and also for drinking and human activities. River water is often the major water source for the sustenance of lives on Earth. However, water in a flowing river suffers loss in dissolved oxygen content because biological organisms consume a good amount of DO as they decompose organic matter in water; likewise, some amount of DO is also consumed for unwanted chemical oxidation of water. Therefore, the dissolved oxygen content continually decreases unless there is oxygen input. Overlying aerial oxygen is continually absorbed by a flowing river. Thus, two opposing factors act on the flowing river water. The biological oxygen demand (BOD) leads to deoxygenation, whereas the absorption of oxygen from the surrounding atmosphere causes reaeration.

Quite often, the condition of river water is monitored by the quantum of the oxygen deficit, which is described by D = DOsat − DOactual, where DOsat represents the saturation value of oxygen that can be dissolved in river water at a particular temperature and DOactual is the actual amount oxygen remaining dissolved in water at a particular place and at a particular time because BOD and COD of the flowing river water are functions of time and position (location).

Rate of change of D varies directly with the rate of change of Lt, the oxygen demand, or the equivalent organic matter at time ‘t’;

$$\begin{gathered} \frac{dL_t}{dt} \propto L_t hence, \frac{dL_t}{d_t} = -k_1 L_t \\ \frac{dD}{dt} = -K_d L_t \end{gathered} \tag{1}$$

Similarly, reaeration or reoxygenation will take place along the flow of a river; essentially, an oxygen deficit is the driving force for reoxygenation and its rate is proportional to D.

$$\frac{dr}{dt} = -k_2\, D \tag{2}$$

$$D = \frac{k_1 L_0}{k_2 - k_1}\left[e^{-k_1 t} - e^{-k_2 t}\right] + D_0 e^{-k_2 t} \tag{3}$$

The equation is known as the Streeter–Phelps equation and is used to for study of water quality.

4.2. Mathematical Modeling Simulation

Oxygen deficit is modeled with the help of the Streeter–Phelps equation, as shown in the preceding paragraph. The prediction of an oxygen deficit with distance and time can aid in the environment management strategy to mitigate the problem of river water quality degradation. To predict the inevitable degradation in water quality with time or flowing distance, the mathematical model of oxygen deficit has been simulated in a MATLAB-Simulink environment. The simulation was carried out over 25 days at any point on the Chambal River within Rajasthan. The water at the entry point of Rajasthan can leave the state by covering a distance of more than 435 km. The protocol used for the mathematical model simulation is shown in Figure 5a. The details of the tasks performed within the Simulink environment are furnished in Figure 5b for better comprehension. The input parameters used for simulating the oxygen deficit as a function of time are shown in Table 3; this is also indicated in the diagrams in Figure 5a. The simulation was first carried out with the available data for 2020 for more than 600 h. The prediction obtained from the above simulation work was then tested for the data available for the year 2021 over a period, which was four times higher than that used for the initial simulation. This was done to establish the authenticity of the prediction that the contemplated mathematical modeling simulation can make.

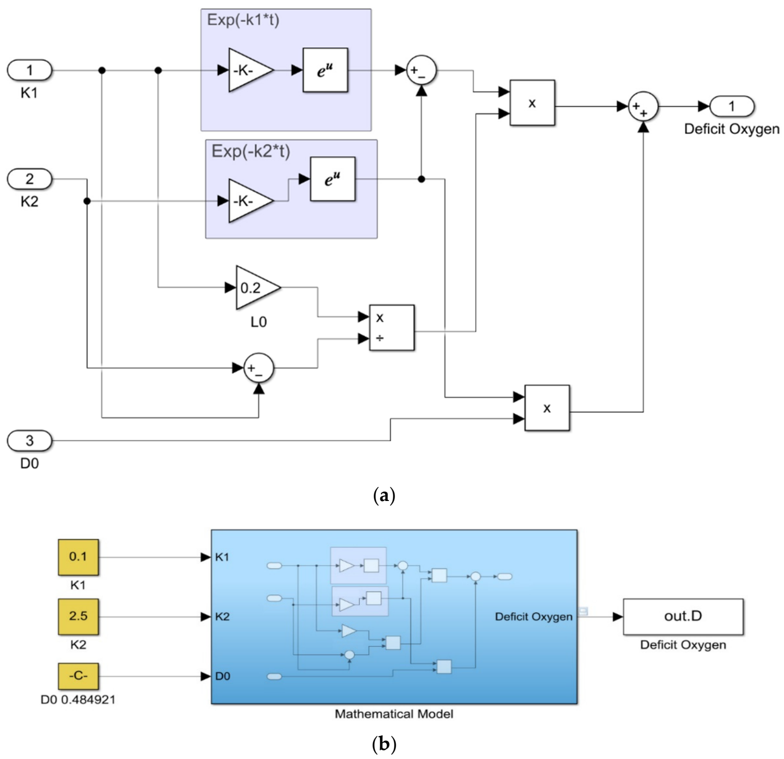


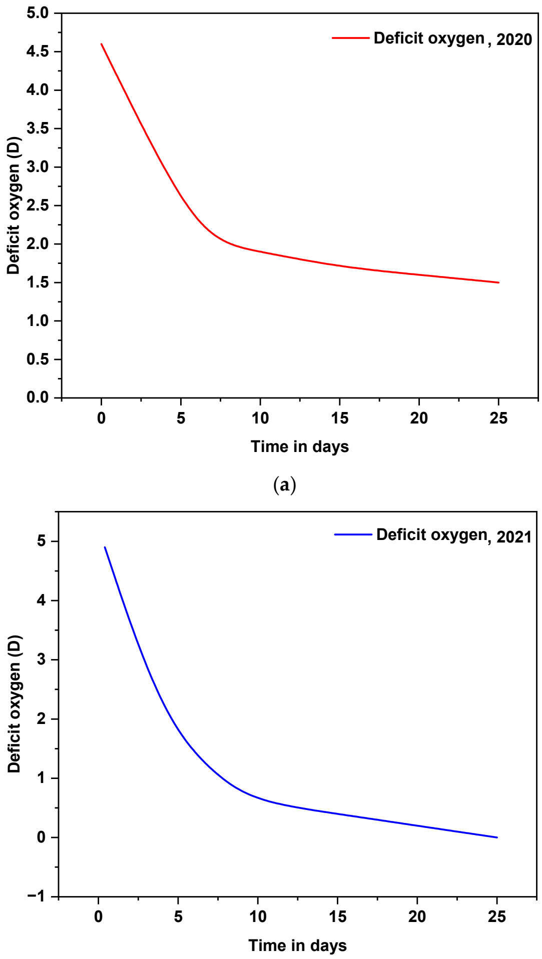
Figure 5. (**a**) Mathematical modeling simulation of oxygen deficit. (**b**) MATLAB Simulink subsystem of oxygen deficit.

Table 3. The input parameters used in the modeling are as follows.

Sr. No.	Parameter	Value
1	K2 (reoxygenation rate constant)	0.1
2	K1 (deoxygenation rate constant)	2.5
3	L0	100
4	D0	4.575714 (for 2020) 4.364286 (for 2021)

4.3. Model Description

The simulation results for the year 2020 are furnished in Figure 6a. It is observed from the figure that the oxygen deficit for the case of Chambal River water decreases with time. This implies that the quality of the river water improves over some time and, beyond this time, it reaches a saturation value. Thus, it is possible to find the critical value of 'D', which is approximately 2 mg/L. Thus, it is noted that the aquatic lives can be sustained if the dissolved oxygen content exceeds 4 mg/L. Now that the dissolved oxygen content in River Chambal is within the safe limit, this has another implication: that the reoxygenation of river water takes place during the flow of the river through the state of Rajasthan.



(a)

(b)

Figure 6. (**a**) Oxygen deficit (D) as a function of time (day) for the year 2020. (**b**) Variation of oxygen deficit with time for the data of 2021 (simulation conducted as per the modeling contemplated for 2020).

The results of the simulations with the similar input variables reveal the same trend of saturation in D value at almost the similar period of time, after which it remains constant. This constancy indicates that there is a balance between deoxygenation and reoxygenation after a definite period of time. Thus, the mathematical modeling simulation carried out in the present investigation is validated. It is interesting to note that the saturation value of the oxygen deficit for 2021 is less than that for 2020, as shown in Figure 6b. This means that the water quality is better in 2021 than in 2020; this may be the result of effective steps being taken to curb water quality degradation.

The comparison of the results of 2020 and 2021 is shown in Figure 7; it is seen in Figure 7 that the saturation value of D is attained within a period of 10 days. Thus, the water of the Chambal River flowing through Rajasthan can regain its quality within a relatively short period. The dissolved oxygen content ought to decrease with the progressive flow of the river because of the oxidation of organic matter, as well as the chemical oxidation caused by inorganic contaminants. However, reoxygenation from the overlying atmosphere takes place simultaneously. The turbulence in flow and the high discharge rate aid in accelerating oxygen absorption. It is also apparent from Figure 6a that the simulation work conducted for 2020 does not differ much from the results of 2021 and this authenticates the efficacy of the present mathematical modeling and simulation work.

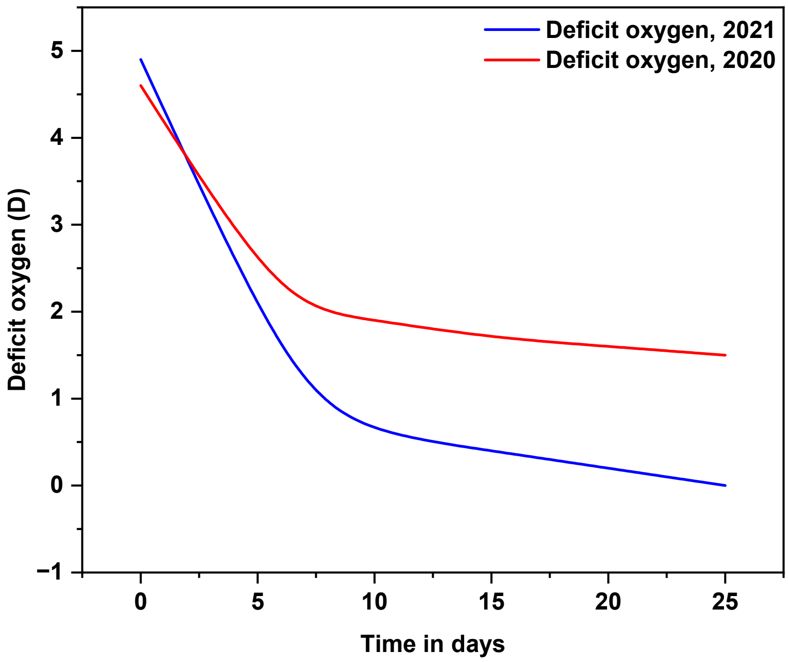


Figure 7. Comparison of simulation results for 2020 and 2021 showing the validity of modeling and simulation of the Chambal River water quality.

5. Conclusions

The authors wish to conclude that the water quality of the Chambal River changes with time and location. Location-specific quality differentials owe their origins to unwarranted human activities. Some important points on the above analysis are given below:

- The multiplied growth of urbanization and industrialization within the Chambal River Basin leads to the discharge of wastes that contaminate the river water.
- The available dissolved oxygen in Chambal River water is adequate for the sustenance of the endangered species living within it.
- The samples from point five, which is the downstream Keshoraipatan region, are due to the overriding influence of agro-based industries, as well as food industries.

- The water quality modeling and simulation results make the authors conclude that the water quality of the Chambal River flowing through Rajasthan can rejuvenate itself during an alarming oxygen deficit within a short period.

The simulation and modeling conducted for 2020 were used for 2021. The consistency of the findings demonstrates the applicability of the modeling and simulation used in the current investigation for later years. Additionally, compared to the year before, the water quality is better in the future in 2021.

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