

**Waste assimilative capacity of coastal waters along Mumbai mega city, west coast of India using
MIKE-21 and WASP simulation models**

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Abstract

Coastal waters are the ultimate receivers of the organic waste materials generated by upstream cities and towns. This waste can cause dissolved oxygen depletion due to increased oxygen demand, affecting the natural ability of water bodies to withstand certain amount of pollution - the Waste Assimilative Capacity. The pollution load (Biochemical Oxygen Demand) calculated using the Population Equivalent value of 0.225 m³/day for the present Mumbai population of 13 million is 731,250 kg/day. Simulations using MIKE-21 and WASP models along with the observed water quality data as well as current meter data indicated that the coastal waters can withstand the present pollution load since the simulated Biochemical Oxygen Demand was within the range of 0.2-1.5 mg/L, the National Standard limits. A projected population increase exceeded the target BOD value of 2 mg/L, indicating the deterioration of ambient quality of coastal waters. Waste Assimilative Capacity studies are crucial in the present-day regional, as well as global issues, such as population explosion, water shortage and climate change.

Keywords: Waste assimilative capacity; water quality; WASP model; biochemical oxygen demand; west coast of India.

1. Introduction

Coastal environments have undergone profound changes over the past the past 150 to 300 years [1]. For nations like India and China, the big changes occurred during recent decades. In North America and Western Europe, the most profound changes in coastal water quality arguably occurred immediately following the industrial revolution, which was > 200 years ago, and around the time when synthetic fertilizers began being used. In addition to natural changes, the coastal environment face multi-dimensional hazards due to anthropogenic fossil fuel combustion, fertilizer use, sewage input, industrial activities, tourism, overfishing, aquaculture farms and marine traffic. Coastal water quality is currently deteriorating due to nutrient loading from sewage wastes. In fact, the largest increase in nutrient loading is predicted for southern and eastern Asia due to the population growth [2]. In these situations, the natural chemical and biological recycling processes of the coastal environment can became overloaded as a consequence of denser population [3]. Hence the population growth emerges as one of the largest contributors of the present coastal water quality deterioration, especially in the southern and eastern Asia.

Coastal water quality problems are subjected to serious debates and concerns among researchers and general public in recent decades due to the direct dynamic relationship of the water quality problems with humans, as well as aquatic ecosystem health, depletion in water resources and increase in water pollution. There are abounding instances [4-7] of irreversible and indelible decline in the ambient coastal water quality around the globe due to unchecked and perpetual release of contaminants. Majority of the causative factors for coastal pollution originate from land-based sources that reach estuaries and the coast via point and non-point sources. The coastal water bodies which ultimately receive the pollutant loads have a natural ability to withstand or assimilate certain amount of pollutants which is termed as the Waste Assimilative Capacity (WAC)/assimilative capacity/carrying capacity/ Self purification [8-10].

The WAC of a coastal environment depends on the hydrodynamics, water quality and land use patterns of the region. Technically, water quality can deteriorate beyond WAC. It is regrettable that WAC becomes most evident when exceeded [11]. Water quality criteria that define the limit of WAC often depend on the type of the water body and its designated use based on water quality standards. Globally, the largest amount of pollution load discharged into the marine environment is sewage [12], which is also the major contaminant discharged to coastal region of India [13]. Sewage being organic in nature is

subjected to bacterial decay resulting in the reduction of oxygen concentration in water and has a high Biochemical Oxygen Demand (BOD). The two most important water quality parameters crucial for the determination of WAC are BOD and Dissolved Oxygen (DO) concentration [14]. The estimation of WAC is done usually by determining the quantitative relationship between pollutant sources and water quality criteria. One of the best tools available for this is a water quality model [15]. Moreover, WAC studies through observation alone are tedious, cumbersome and expensive. Modeling the marine environment is cost effective as it can reveal the hydrodynamics and other related processes well before investment decisions are made and costly field studies are conducted [16].

MIKE21 HD is a hydrodynamic model developed by Danish Hydraulic Institute, Water & Environment [17]. MIKE21 has regularly been used as a tool to model hydrodynamic problems of various complexities [18]. The model has been used earlier to study the circulation characteristics off Mumbai during an extreme event [19], modelling of tide driven currents and eddies [20] and residence time of pollutants in gulf of kachchh [21] along west coast of India. The model uses equations of conservation of mass and momentum, integrated over the vertical to describe the flow and water level variations. The Water Quality Analysis and Simulation Program (WASP) model [22-25] is a validated water quality model, the development of which was supported by United States Environmental Protection Agency (US-EPA). WASP has been utilized in addressing major water quality problems around the globe [26-32]. After many versions (33-37), the latest enhanced version of the model is WASP 7 and includes kinetic algorithms for eutrophication/conventional pollutants, organic chemicals/metals, mercury, temperature, fecal coliform and conservative pollutants. The model can interpret and predict water quality scenarios in response to natural as well as anthropogenic pollution of various environments. The model is a dynamic compartment modelling program and can be one, two or three dimensional depending on the complexity of the intended use. The WASP model follows the box modelling approach. The boxes can be fitted to any morphometry. The two kinetic sub-models simulate two of the major classes of water quality problems: conventional pollution which involves dissolved oxygen, biochemical oxygen demand, nutrients, eutrophication and toxic pollution which involves organic chemicals, metals, and sediment [38, 25]. The basic principle of the water-quality model is the conservation of mass. The water volume and water-quality constituent masses being studied are tracked and accounted for over time and space using a series of mass balancing equations and to perform these mass balance computations, data defining seven important characteristics should be given as input to the WASP model namely 1) simulation and output control, 2) model segmentation, 3) advective and

dispersive transport, 4) boundary concentrations, 5) point and diffuse source waste loads, 6) kinetic parameters, constants, and time functions and 7) initial concentrations [39, 25]. The input data, together with the general mass balance equations and the specific chemical kinetics equations, uniquely define a special set of water quality equations and are numerically integrated by WASP as the simulation proceeds in time. At user-specified print intervals, the model saves the values of all display variables for subsequent retrieval. These programs allow the user to interactively produce graphs and tables of variables of all display variables [25]. The WASP modelling frame work is found to be suitable for DO/BOD applications and WAC studies [40].

The present study assesses the WAC considering BOD generated by both the present and future population and the associated processes along the coastal region of Mumbai by using the validated WASP model.

2. Materials and Methods

Urbanization has created the phenomenon of megacities: urban areas with a population of 10 million or more [41]. Megacities are one of the biggest generators of domestic and industrial wastes in all types and forms [42]. Mumbai (Figure 1), situated in the state of Maharashtra along the west coast of India, is a coastal megacity, as well as the commercial and entertainment capital of the country. Coastal cities contrive to spread their transformative influence both into the hinterland, along the coastline, and into the coastal waters themselves [43]. The urban population of India has grown nearly five fold during the last 50 years [44], while the total population of the country doubled. The opening of Thane Creek, the largest natural harbor on India's west coast, is protected by a 650 km² island extending into the Arabian Sea and is now almost entirely urbanized by present-day Mumbai [45]. The Mumbai region is divided into two administrative blocks – the Mumbai city and the Mumbai sub-urban. Along with the elevated population, the region is also heavily industrialized, which adds other pollutant loading to the region. Approximately 60% of residents of the region live in squatter settlements [46-47], which have no provision of treatment of waste water generated, as of now. Since the location of the region is on the west coast of India, waste water emanating from the adjacent urban and squatter settlement areas finds its way into the coastal waters through open drains which connect to rivers in the region ultimately draining to the coastal ocean. Lack of adequate sanitation facilities in the region also contribute to waste materials discharged to the coastal waters. Though Sewage Treatment Plants (STPs) are installed in specific locations, they are inadequate to handle the present situation. According to a World Bank report,

about 75% of the sewage in this region is untreated and discharged to local rivers and coastal waterways, causing extensive environmental hazards [48]. The present study considered the effluents generated by both the administrative blocks of the Mumbai region, which include the urban area and squatter settlements. We also assume a hypothetical scenario in which all the effluents generated will ultimately reach coastal waters.

The hydrodynamic input for the water quality model during October, 2009 – January 2010 is resolved from the output of MIKE21 HD. The hydrodynamic model domain covers the Mumbai coastal region (18° 30' N - 20° N and 71° 45' E - 73° 15' E) of 330 x 330 grids having a resolution of 500m x 500m (Figure 1c). The model bathymetry was generated using ETOPO5 data obtained from the National Geophysical Data Center, USA for deep waters and digitized hydrographic chart data [49] for the nearshore regions. The south, west and north boundaries of the domain were driven by the tidal elevations predicted using the Global Tide Model [50-52]. The six hourly blended wind data of Quick Scatterometer (QuikSCAT) and operational European Centre for Medium-Range Weather Forecasts (0.25° x 0.25°) [53] obtained from IFREMER/CERSAT [54] was used for hydrodynamic simulation. The wind vectors were linearly interpolated to each grid cell. The model output was validated with the zonal and meridional current velocities derived from the surface current speed and direction measured using Aanderaa Recording Current Meters (RCM 9 LW) at two nearshore locations off Satpati and Worli along the Mumbai coast at 15 m water depth during 22 October – 22 November, 2009 at 10 minute interval. The RCM 9 LW has an accuracy of ± 0.15 cm/s for current speed and $\pm 7.5^\circ$ for current direction. The output parameters of fluxes, water levels and current velocities were obtained for every 10 minutes. We used the output parameters of MIKE21 (hydrodynamics) as input for the water quality model, WASP.

The waste-water load of the study area was calculated in terms of BOD using a Population Equivalent (PE) value of 0.225 m³/day [55]. This value is conventionally used for developing countries, considering the whole effluents ultimately reach the coastal waters. PE is the hydraulic or flow equivalent to the contribution from one person per day. The standard PE of the US-EPA is 0.284-0.378 m³/day, while a 0.19 m³/day was suggested [56] for the developing countries. Since 75% of the waste-water in Mumbai is untreated, the remaining 25% is treated or partially treated by STPs. We have estimated the flow weighted average of treated effluents in terms of BOD from STPs, and the final effluent load is calculated by summing the PE and STP generated loads. The effluent loads for the strong (400 mg O₂/L), medium (250 mg O₂/L) and weak (110 mg O₂/L) classes of sewage are calculated (Table1),

which are the conventional classification of sewage types [57]. The three cases are incorporated into the model separately to crosscheck the class of sewage, which shows compatibility with the observed BOD values. The effluent load is calculated using the following equations.

$$\text{Effluentload} = \{ \text{TotalPopulation} * P.E * (1\text{Day} / 24\text{hours}) * (1\text{hour} / 3600\text{sec}) * (\text{EffluentQuality}) * 86.4 \} \text{Kg} / \text{day}$$

----- (1)

$$\text{TotalEffluentLoad} = 75\%(\text{UntreatedEffluents}) + 25\%(\text{Treatment})$$

----- (2)

The calculated load was given as input to the model in specific locations where the effluents are released into coastal waters in real time to understand the prevailing assimilative capacity behavior of the region. It may be noted that we considered only the domestic sewage generated in the area. Domestic wastewater generated in and around Mumbai enters the Arabian Sea, directly or via creeks, bays and estuaries.

The WASP model domain is between Satpati and Worli which covers an area of 1215 km² with 135 grids of 3km x 3km resolution. The region is divided into upper, middle and lower sectors, each having an extension of 27 km (Figure 1). The present area of study, Mumbai comes in the lower sector of the model domain. The model was calibrated using measured Conductivity-Temperature-Depth, currents, water quality data, as well as the coefficients and constants relevant to the study area. The details regarding CTD data is given in the tables 2-4. The model was utilized for the simulation of BOD during October, 2009-January, 2010. Further, the model results are validated with the DO and BOD data collected at 18 stations (Figure 1c) along the Mumbai coast during October, 2009. The surface and bottom samples were collected using a Niskin sampler. Soon after collection, the water samples were fixed for DO and were determined by Winkler's method [58]. Samples for the determination of BOD were collected in triplicate. DO concentration was determined first by using one of the triplicate samples according to the Winkler's method. The remaining bottles are then left for 5 days in the dark at 20°C. DO in these samples were determined by Winkler's method after fixing the samples immediately on completion of the 5 day incubation period. The BOD is computed from the initial DO concentration [59].

We also used population data from the 2011 Indian national census [60]. In addition to this, the Mumbai population data from Taubenböck *et al.* (2009) was used to project annual population growth per year and percentage growth for the years 2020, 2050 and 2100 (Table 5). The future population changes were calculated using two methods: (i) percentage population growth per annum (mean growth) and (ii) linear

extrapolation. The BOD was simulated for the sewage emanated by the present population as well as for future populations in order to understand the effect of population along the Mumbai coastal waters.

3. Results and discussion

The Mumbai city and suburb are one of the most heavily populated coastal regions on earth. The total population according to the latest national census in Mumbai region is around 13 million. The number of Megacities in the world increased from 3 in 1975 to 19 in 2007. Future projections predict this figures will be 24 in 2015 and 27 in 2025 [61]. According to United Nations Department of Economic and Social Affairs [62], Mumbai ranked 7th in terms of population in 2011. Future projections for the year 2025 indicated that the region is ranked 4th, ahead of New York, Mexico City and Sao Paulo with Tokyo, Delhi and Shanghai occupying first, second and third place in the list respectively. According to the projections, we can speculate that the population difference between Tokyo and Mumbai decreased from 17.5 million in 2011 to 12.1 million in 2025, indicating higher rate of population growth in Mumbai than the most populous city. As the cities grow and flourish, the demand of water for domestic, industrial purposes surges and simultaneously, the problems of waste water and sewage also arise. From literature, it is evident that effluents from Mumbai region have medium quality and the incorporation of three cases of effluent quality (weak, medium, strong) also show results which are in par with the earlier studies [63-64] indicating medium sewage quality. The model BOD output for the medium quality effluents shows good comparison with observed BOD values in the region. The model underestimates the BOD values in the case of weak effluents and overestimates in the case of strong effluents, when compared to observed BOD values. The flow weighted average BOD after effluent treatment (by STPs) is calculated as 113.5 mg/L. The effluent load, calculated for different classes of sewage, generated by the total population, is given in the Table 1. The total untreated effluent load in terms of BOD for the present population is resolved as 731,250 kg/day BOD for sewage having medium quality and after considering the treatment by STPs the effluent load assumed is 631,391 kg/day BOD. The validation results of the zonal and meridional currents are shown in figures 2 and 3. The scatter plot between measured and simulated current velocities (Figure 4) shows that the parameters are least scattered, indicating less variations between observed and modeled values. The correlation coefficient, r.m.s. error and bias estimated for u-velocity are 0.63, 0.07 and 0.01, respectively, off Satpati and 0.73, 0.10 and 0.00, respectively, off Worli, whereas those estimated for v-velocity are 0.89, 0.28 and 0.00,

respectively, off Satpati and 0.86, 0.17 and 0.04, respectively, off Worli. The correlation coefficient for u-velocity is less compared to that of correlation coefficient for v-velocity and the zonal velocity component is much lower compared to meridional components. The regression analysis between the observed and modeled DO and BOD for surface water is presented in Figure 5 which reflects the strong confidence in the model. Regardless of the low BOD values, low DO values are observed at some stations (Table 6). The observed DO values ranges from a low of 1.48 to a high of 7.17 mg/l (av.4.61 mg/l) in surface, while from 0.67 to 4.67 mg/l (av.1.79 mg/l) in the bottom, indicating significantly low values in bottom water layer. Hypoxic condition (DO less than 2-3 mg/L) prevails in the bottom waters of almost all the stations with severe hypoxia observed at the off shore stations (Stations: 1, 6, 9, 10, 15& 18). Surface DO values seem to be increasing from south to north, as the effect of sewage pollution decreases from south to north (Mumbai is near the northern most stations).

The simulated BOD attributed to the present population in the coastal waters of Mumbai is presented in Figure 6. Though the region is documented for heavy metal pollution [65] and Petroleum Hydrocarbons (PHCs) [66], our results testify that for BOD, Mumbai coastal region can assimilate the waste generated by present population, since the BOD values (0.2 – 1.5 mg/L) are within the limit proposed by Central Pollution Control Board, India (CPCB). In spite of the teeming population, the modeling exercise of the Mumbai region reveals that the coastal waters can assimilate the waste generated by the present population due to the specific hydrodynamic conditions prevailing in the region. The water quality of the Mumbai region balances between the fluxes of pollutants received and their dispersion by tidal flushing as well as their decay and removal from the water column by processes such as degradation, adsorption on suspended solids, sedimentation and biotic uptake [67].

During the simulation period, the temporal changes in water quality pattern reveal interesting features. The Mumbai coastal region encountered the tropical cyclone, Phyan (9-11 November 2009) within the simulation period. The physical and biological response of the Arabian Sea due to the cyclone [68] and coastal circulation during the event was already investigated by other authors. The effect of the cyclone is clearly seen in the residual currents of the region (Figure 7). Modeled BOD values were higher during the pre-cyclone with a maximum value of 1.4 mg/L, then decreased to a minimum of 0.2 mg/L during the cyclone and increased thereafter showing a pattern that followed the tidal cycle. The decrease in BOD may be due to the enhanced mixing induced by the increased wind stress. The occurrence of high rainfall during the cyclone period could also dilute the BOD concentration. Other phenomenon such as decrease in sea surface temperature during cyclones can also induce lower BOD values, since oxygen

solubility is higher for cold water. This will enhance the availability of oxygen in the water column and corresponding increase in WAC. The indication is that extreme events can increase the WAC of marine environment, however only for a short period. The high primary productivity during post-cyclone can have a negative effect on WAC, due to consumption of the available oxygen for the subsequent decay of organic detritus, as well as introduction of more organic detritus. The tidal currents dominate [69] over the wind driven currents around the Mumbai coastal waters. Simulations done by incorporating the pollutant load calculated from present population of the region show that the BOD values respond inversely to the tidal variations (Figure 8). During high tides the BOD values exhibit a decrease in concentration. After the cyclone, BOD follows the tidal variations as mentioned in the above discussion. The BOD values simulated for the middle sector in the model domain also shows the same response as that of the lower sector. This effect of the pollutant load is not visible in the upper sector. The reason could be that the hydrodynamic conditions are such that pollutant load gets dispersed before reaching the upper sector. Dispersion pattern of the region is discussed in detail by other authors [70]. Some authors [71] even defined the WAC in the context of dispersion as loading which properly disperses throughout the receiving domain without harming the health of the ecosystem.

Population pressure cause changes in the surface water dynamics and decline in the extent of open water [72], which are pathways of waste materials to coastal waters. The population increase is responsible for the degradation of coastal ecosystems inducing serious environmental consequences [73-75]. Though many studies [76] attribute a future population explosion in the region, the recent Government of India census indicates a negative population growth (-5.75%) for the Mumbai city. Since the population of Mumbai region has almost doubled in a short span of past 20 years [77], it is expected that the trend may continue in future as well [78]. The annual population growth per year and percentage growth for the years 2020, 2050 and 2100 are shown in the Table 5. The annual and percentage population growth rate is represented by the Figure 9a and the projected future population growth is represented by the Figure 9b. Though the projection shows decrease in both growths per year and percentage growth, population seems to double by 2050. Therefore, as a second case study, we considered a typical scenario when the present population is doubled to check whether an increase in population will adversely affect the WAC of the coastal waters or not (keeping the present hydrodynamic conditions). The scenario is considered by keeping a target value of 2 mg/L BOD. However, it may be noted that the Arabian Sea is experiencing a regional climate shift [79-80] that can potentially alter the circulation and hydrodynamics of the region in future, which we do not address in this model. Figure 10 presents the simulated BOD

values for the doubled population. The BOD values show substantial increase (up to 3 mg/L) when the pollutant load is increased. From the results obtained we can decipher that the BOD load is exceeding the target value of 2 mg/L. This clearly indicates that population increase can result in the exceedence of pollutants, which will surpass the WAC of coastal waters. This will exert additional pressure to already pressurized coastal zone, implying its severe vulnerability in near future. The upper sector in this case also does not show the effect of pollutant load as it was in the earlier simulation.

In addition to these changes the WAC of coastal waters around India can change intra-annually as the coastal currents change direction with season [81]. The coastal current along the west coast of India, the West India Coastal Current (WICC), one of the two eastern boundary currents which flow against the winds [82] is southward during June to September and northward during November to January. The uniqueness in the current regime will have many implications regarding the WAC of the region compared to other coastal areas. The present study is done only for a period of four months which gives only a partial understanding of the seasonal WAC behavior of Mumbai region. More data of this kind is required to understand this aspect in detail.

4. Conclusion

WAC of the coastal waters of Mumbai, one of the major global megacities has been discussed using measured data and numerical simulations. The study indicates that the population rise can be a causative factor for increased effluent discharge into the coastal waters. This can bring about potential ill-effects on marine food webs and the availability of the marine resources which the coastal population depend upon. Therefore, WAC studies are of utmost importance in our world of soaring population and increasing demand for depleting water resources. The present study also point out the need for more STPs in the region to handle the waste water generated by the soaring population. Moreover such studies will help to take major decisions on maintaining sustainable resource utilization as well as a healthy coastal ecosystem.

Apart from the WAC studies, mitigation and adaptation regimens will be laudable in the coming decades of resource depletion and population explosion. Since the littoral population in megacities is more vulnerable to water quality deterioration and associated predicaments than other communities, implementation of scientifically backed technological solutions together with sustainable land use and public education will alleviate the adverse impacts to some extent and can inhibit undesirable shifts in ecosystem regimes. In addition to regular field observations, modeling studies should be practiced to

follow stringent water quality standards. To optimize the energy consumption by STPs and attain environmental friendliness, green technologies which are prevalent in water and waste water treatment industries should be adopted. Nonetheless public policy and environmental laws are crucial factors for mitigation and adaptation strategies in environmental problems.

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Figure captions

Figure 1. Study area: (a) The box indicate the study area (b) Study area in high resolution (c) Bathymetry and station locations

Figure 2. Validation of U component of currents: (a) off Worli and (b) off Satpati

Figure 3. Validation of V component of currents: (a) off Worli and (b) off Satpati

Figure 4. Scatter of measured and modelled current velocities: (a) u-velocity off Satpati, (b) u-velocity off Worli, (c) v-velocity off Satpati and (d) v-velocity off Worli

Figure 5. Regression analysis of model values with measurements: (a). DO and (b). BOD

Figure 6. Simulated BOD for the present Mumbai population for the lower and middle sector

Figure 7. Total, tidal, residual current velocities measured off Mumbai: a) u-velocity off Worli, b) u-velocity off Satpati, c) v-velocity off Worli and d) v-velocity off Satpati

Figure 8. Predicted tidal levels of Mumbai coastal region

Figure 9. Population growth: (a). Annual growth per year and percentage growth and (b). Future population growth

Figure 10. Simulated BOD for an increase in population, with the present coastal hydrodynamics for the lower and middle sector, The red line indicates the target value (2 mg/L).

Table Captions

Table 1. Sewage classification and pollution load

Table 2. Details of CTD measurements

Table 3. CTD measurements (Stations 1 - 9)

Table 4. CTD measurements (Stations 10 - 18)

Table 5. Population growth: Average projected population growth

Table 6. Surface and bottom DO & BOD

Table 1. Sewage classification and pollution load

Classification of sewage Contamination	Concentration of BOD (mg/L)	Pollutant Load (kg/day)	Pollutant Load (kg/day) after Treatment
Strong	400	1170001.15	960453.86
Medium	250	731250	631391
Weak	110	321750.32	-----

Table 2. Details of CTD measurements

Station No.	Location	Transect Position	
		Latitude	Longitude
1, 2, 3	Off Mahim	18°59.986'N	72°42.6'E
		19°05.096'N	72°48.096'E
		19°00.297'N	72°47.639'E
4,5,6	Off Santacruz	19°05.096'N	72°48.096'E
		19°05.002'N	72°44.648'E
		19°04.591'N	72°43.380'E
7,8,9	Off Versova	19°10.443'N	72°46.058'E
		19°10.639'N	72°41.945'E
		19°09.973'N	72°37.951'E
10,11,12	Off Manori	19°15.072'N	72°37.402'E
		19°15.242'N	72°41.719'E
		19°15.051'N	72°45.607'E
13,14,15	Off Vasai	19°20.235'N	72°44.964'E
		19°20.171'N	72°40.384'E
		19°20.207'N	72°35.696'E
16,17,18	Off Arnala	19°25.052'N	72°44.28'E
		19°25.0'N	72°40.685'E
		19°25.0'N	72°35.811'E

Table 3. CTD measurements (Stations 1 - 9)

Station 1	Depth (m)	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
	Temperature(°C)	27.11	27.02	26.65	25.93	25.7	25.69	25.68	25.67	25.67	25.67	25.67	25.66	25.65	25.65	25.65	25.65
	Salinity (PSU)	35.58	35.59	35.73	36.04	36.16	36.16	36.16	36.16	36.16	36.16	36.16	36.16	36.16	36.17	36.17	36.17
Station 2	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	6.00	8.00	9.00	10.00	11.00	----	---	---	---
	Temperature	27.20	27.12	26.98	26.41	26.21	26.19	26.17	26.16	26.16	26.15	26.15	26.15	---	---	---	---
	Salinity	35.36	35.50	35.58	35.94	36.07	36.09	36.10	36.11	36.11	36.11	36.11	36.11	---	---	---	---
Station 3	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	---	---	---	---	---	---
	Temperature	28.02	27.97	27.32	27.07	27.05	26.74	26.49	26.41	26.38	26.44	---	---	---	---	---	---
	Salinity	35.20	35.17	35.33	35.58	35.63	35.69	35.89	35.94	35.93	31.63	---	---	---	---	---	---
Station 4	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	---	---	---	---	---	---	---	---	---
	Temperature	27.77	27.17	26.87	26.65	26.60	26.59	26.60	---	---	---	---	---	---	---	---	---
	Salinity	34.47	35.34	35.58	35.65	35.71	35.72	35.72	---	---	---	---	---	---	---	---	---
Station 5	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	---	---	---	---
	Temperature	27.83	27.78	27.67	27.30	26.33	26.08	26.04	26.03	26.03	26.03	26.03	26.03	---	---	---	---
	Salinity	35.26	35.26	35.27	35.33	35.79	36.03	36.06	36.06	36.06	36.06	36.05	36.05	36.05	---	---	---
Station 6	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	---	---	---	---
	Temperature	27.67	27.68	27.62	27.10	26.58	26.04	25.94	25.89	25.86	25.86	25.85	25.85	---	---	---	---
	Salinity	35.26	35.50	35.50	35.52	35.69	36.03	36.09	36.10	36.10	36.10	36.10	36.10	---	---	---	---
Station 7	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	---	---	---
	Temperature	27.37	27.23	27.07	26.99	26.19	25.66	25.58	25.56	25.54	25.53	25.53	25.52	25.50	---	---	---
	Salinity	34.09	35.21	35.34	35.39	35.66	36.03	36.09	36.09	36.09	36.09	36.09	36.09	36.09	36.09	---	---
Station 8	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	---	---	---
	Temperature	26.91	26.77	26.73	26.49	26.09	26.06	26.06	26.05	26.04	26.04	26.04	26.04	26.04	---	---	---
	Salinity	34.09	35.26	35.36	35.56	35.95	35.98	35.98	35.99	35.99	35.99	35.99	35.99	35.96	34.20	---	---
Station 9	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00
	Temperature	26.84	26.75	26.65	26.30	25.80	25.75	25.75	25.74	25.74	25.74	25.74	25.74	25.74	25.73	25.73	25.73
	Salinity	33.78	34.95	34.99	35.35	35.87	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97

Table 4. CTD measurements (Stations 10 - 18)

Station 10	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	---
	Temperature	26.84	26.75	26.65	26.30	25.80	25.75	25.75	25.74	25.74	25.74	25.74	25.74	25.73	25.73	25.73	25.73	---
	Salinity	33.78	34.95	34.99	35.35	35.87	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	35.97	---
Station 11	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	---	---	---	---	---	---
	Temperature	27.94	27.30	26.78	26.23	26.09	26.08	26.07	26.07	26.07	26.07	26.07	---	---	---	---	---	---
	Salinity	34.70	34.74	35.05	35.54	35.77	35.80	35.79	35.79	35.79	35.79	35.79	---	---	---	---	---	---
Station 12	Depth	1.00	2.00	3.00	4.00	5.00	6.00	---	---	---	---	---	---	---	---	---	---	---
	Temperature	28.37	27.06	26.82	26.69	26.69	26.76	---	---	---	---	---	---	---	---	---	---	---
	Salinity	34.75	35.16	35.35	35.43	35.42	33.96	---	---	---	---	---	---	---	---	---	---	---
Station 13	Depth	1.00	2.00	3.00	4.00	5.00	6.00	---	---	---	---	---	---	---	---	---	---	---
	Temperature	28.18	27.11	26.66	26.61	26.61	27.46	---	---	---	---	---	---	---	---	---	---	---
	Salinity	32.43	33.01	34.74	35.31	35.32	29.37	---	---	---	---	---	---	---	---	---	---	---
Station 14	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	---	---	---	---	---
	Temperature	27.84	27.76	27.09	26.33	26.23	26.20	26.17	26.15	26.14	26.15	26.15	26.15	---	---	---	---	---
	Salinity	34.21	34.25	34.72	35.55	35.66	35.66	35.66	35.67	35.67	35.67	35.67	35.66	---	---	---	---	---
Station 15	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
	Temperature	28.07	28.01	27.20	26.65	26.38	25.91	25.82	25.78	25.76	25.73	25.71	25.70	25.70	25.70	25.70	25.70	25.71
	Salinity	34.66	34.99	34.95	34.95	35.16	35.44	35.74	35.82	35.84	35.85	35.86	35.86	35.86	35.86	35.86	35.86	35.86
Station 16	Depth	1.00	2.00	3.00	4.00	5.00	---	---	---	---	---	---	---	---	---	---	---	---
	Temperature	27.88	27.14	26.98	26.89	26.87	---	---	---	---	---	---	---	---	---	---	---	---
	Salinity	33.46	34.35	34.86	35.24	35.29	---	---	---	---	---	---	---	---	---	---	---	---
Station 17	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	---	---	---	---	---	---
	Temperature	27.41	27.22	27.11	26.87	26.75	26.72	26.70	26.70	26.69	26.69	26.69	---	---	---	---	---	---
	Salinity	33.95	34.69	34.75	35.26	35.60	35.65	35.65	35.65	35.65	35.65	35.65	---	---	---	---	---	---
Station 18	Depth	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	---
	Temperature	28.71	27.91	27.58	27.16	26.72	26.43	26.38	26.37	26.36	26.34	26.34	26.33	26.33	26.33	26.32	26.32	---
	Salinity	34.41	34.79	34.96	35.17	35.51	35.74	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.79	35.78	---

Table 5. Population growth: Average projected population growth

Year	%Growth Rate		Linear extrapolation	
	Mean Increase In Population	Projected Population (in million)	Projected population (in million)	Average population (in million)
2020	0.16	25.36	23.61	24.48
2050	1.12	46.28	34.8	40.54
2100	2.71	81.15	53.46	67.31

Table 6. Surface and bottom DO & BOD

Station	Depth	Surface DO (mg/L)	Bottom DO (mg/L)	Surface BOD (mg/L)	Bottom BOD (mg/L)
1	19	4.43	1.31	1.27	0.65
2	13	3.12	2.63	1.79	1.63
3	6.5	2.79	1.48	1.79	1.14
4	6.5	1.48	0.82	0.31	0.32
5	14.2	3.78	4.27	0.94	1.10
6	15	4.76	1.97	1.26	0.14
7	8	2.50	3.17	0.83	1.83
8	14	3.33	2.00	0.70	0.67
9	17	5.83	0.67	0.67	0.33
10	16	4.5	4.67	0.67	0.83
11	11	5	1.33	1	0.33
12	8	5.5	0.83	1.33	0.5
13	7	6.17	1.50	1.17	0.33
14	12	5.50	1.33	1.00	0.67
15	18	7.17	0.67	2.00	0.00
16	6	5.33	1.50	1.00	0.00
17	10	5.33	1.00	1.50	0.17
18	15	6.50	1.17	1.17	0.00

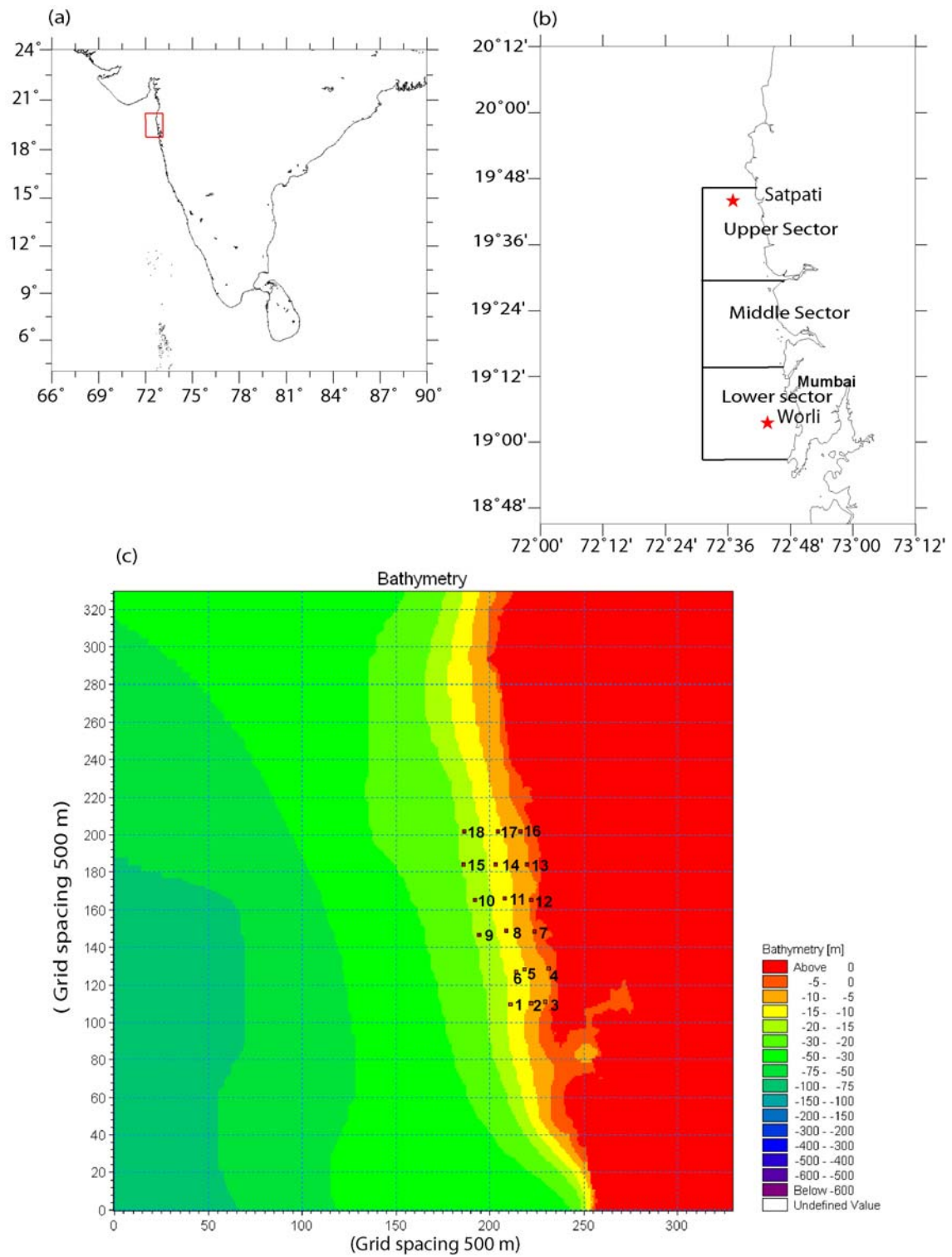


Figure 1.

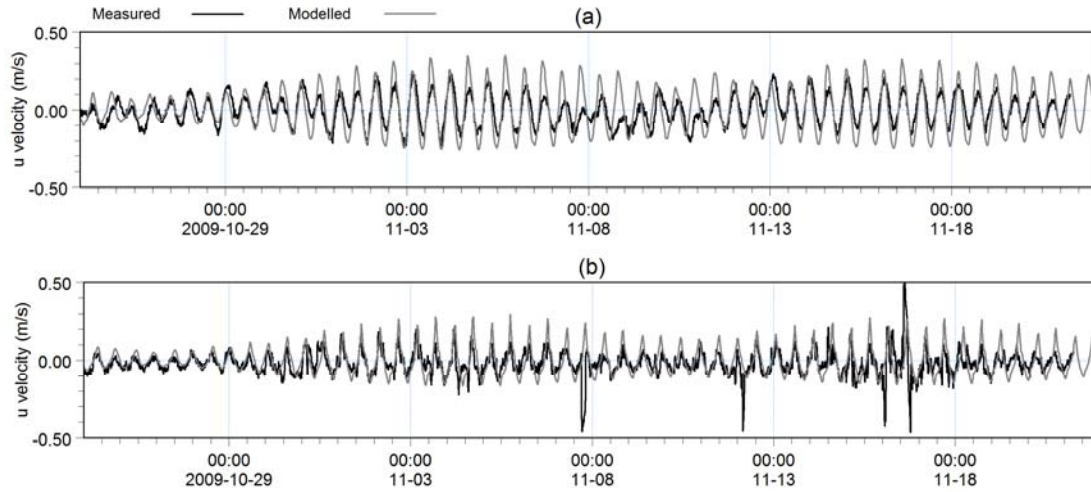


Figure 2.

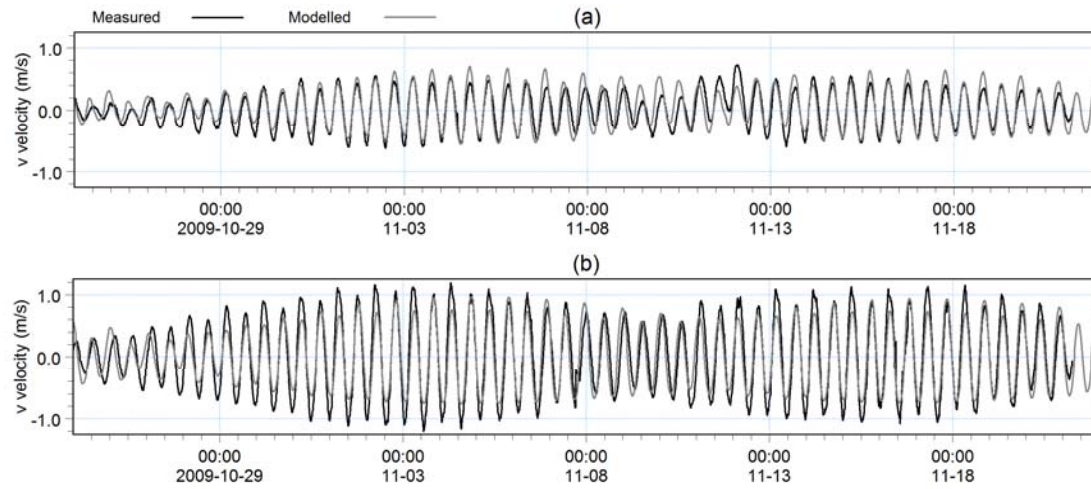


Figure 3.

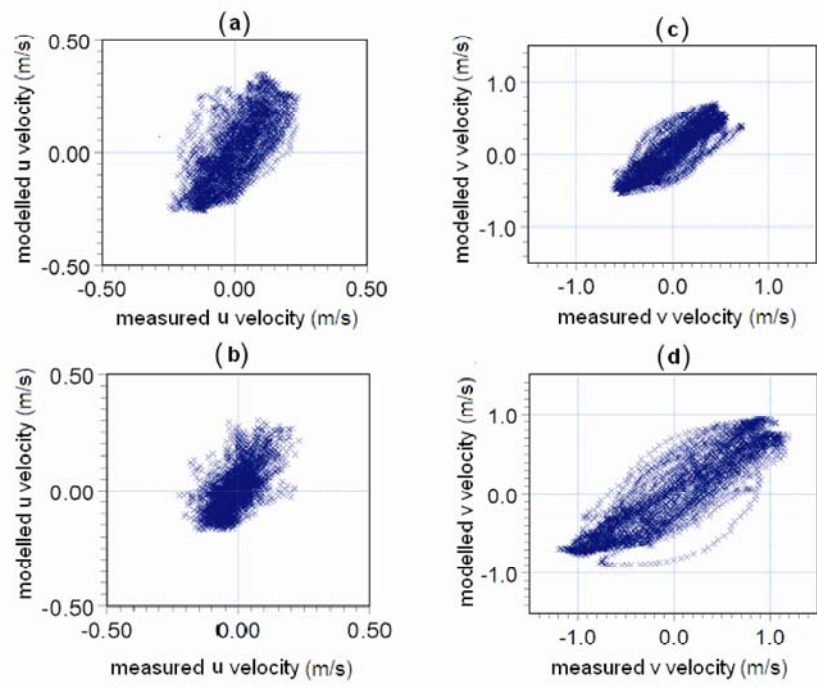


Figure 4.

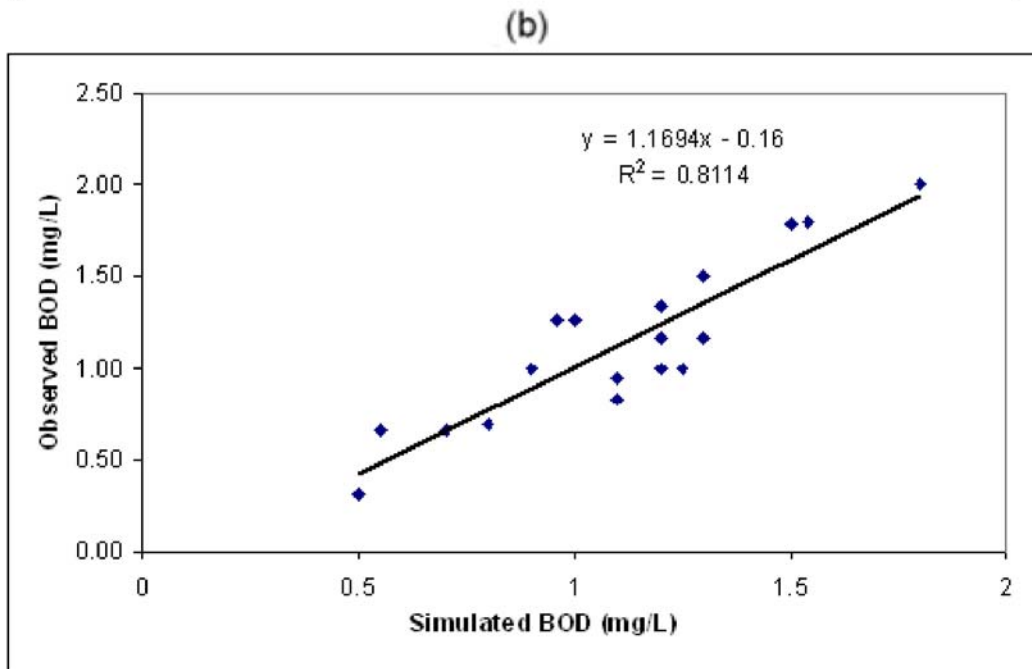
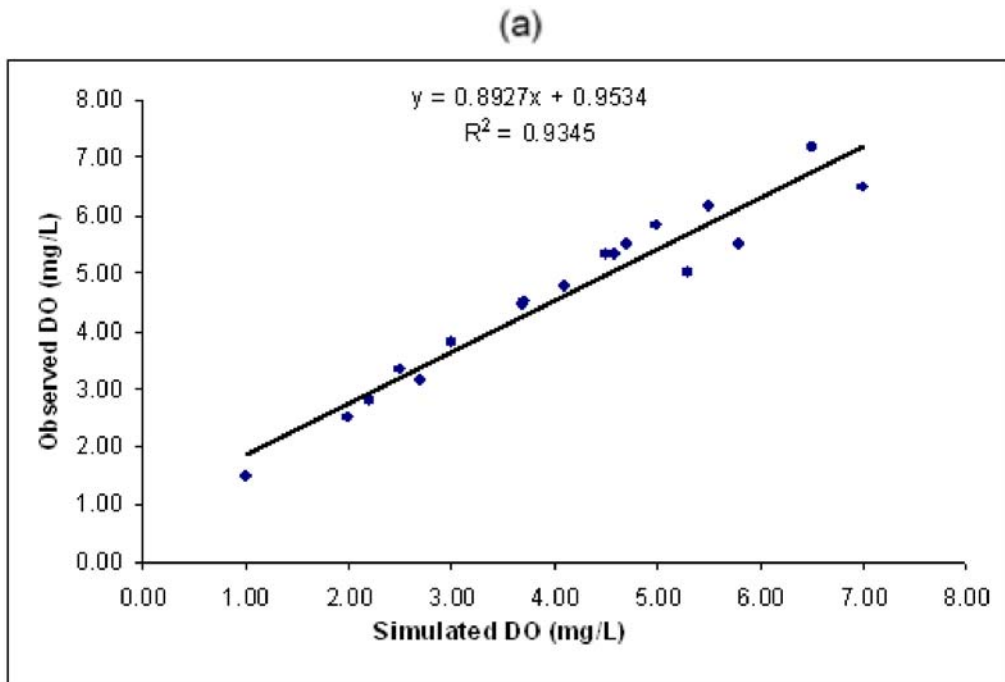


Figure 5.

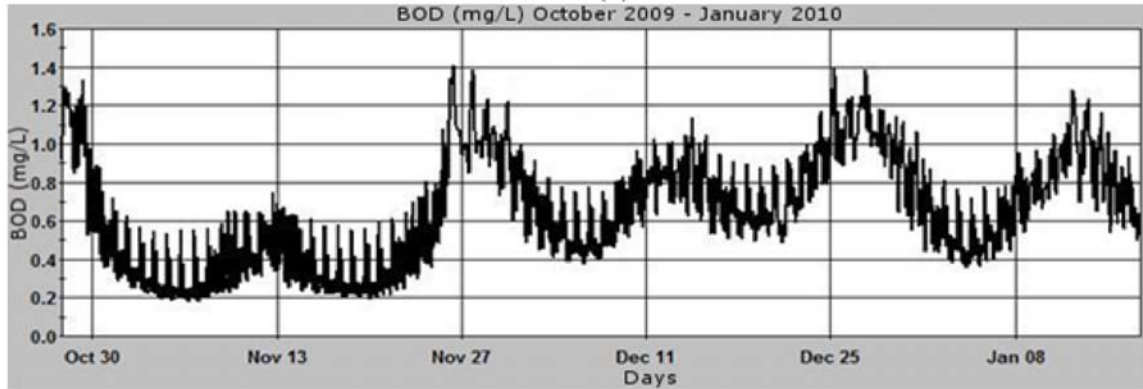


Figure 6.

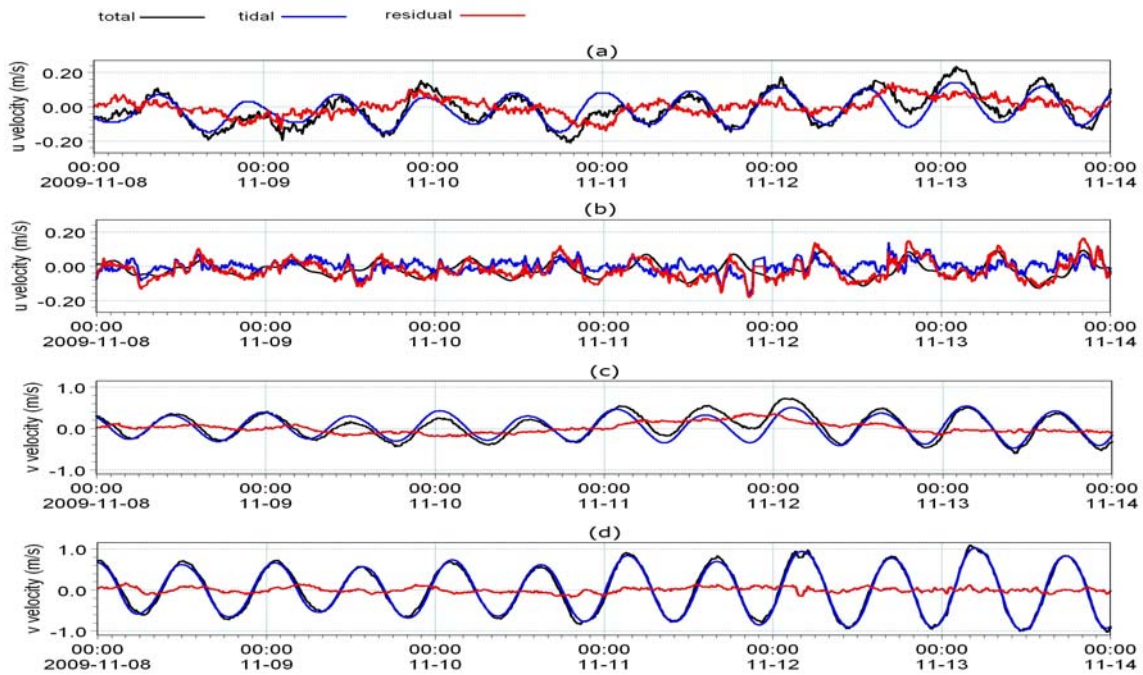


Figure 7.

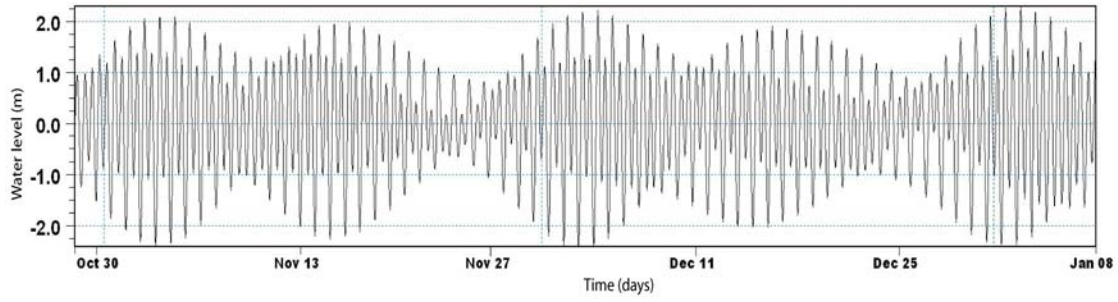


Figure 8.

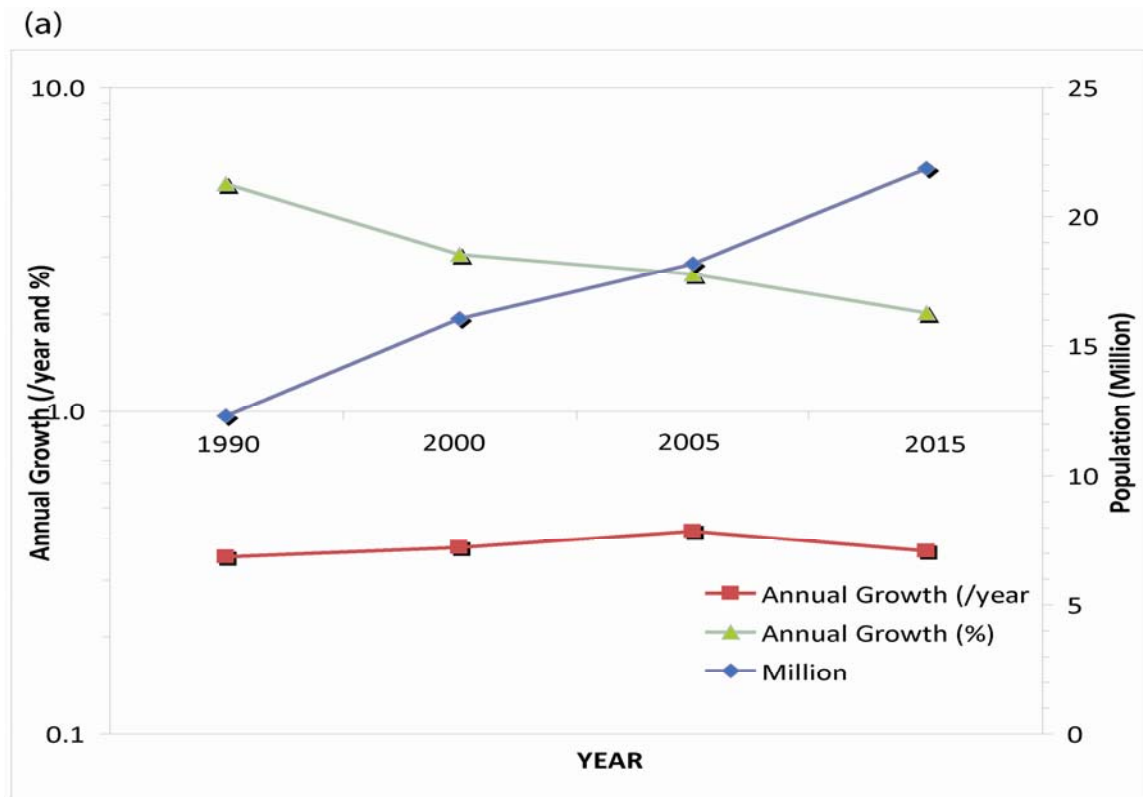


Figure 9a.

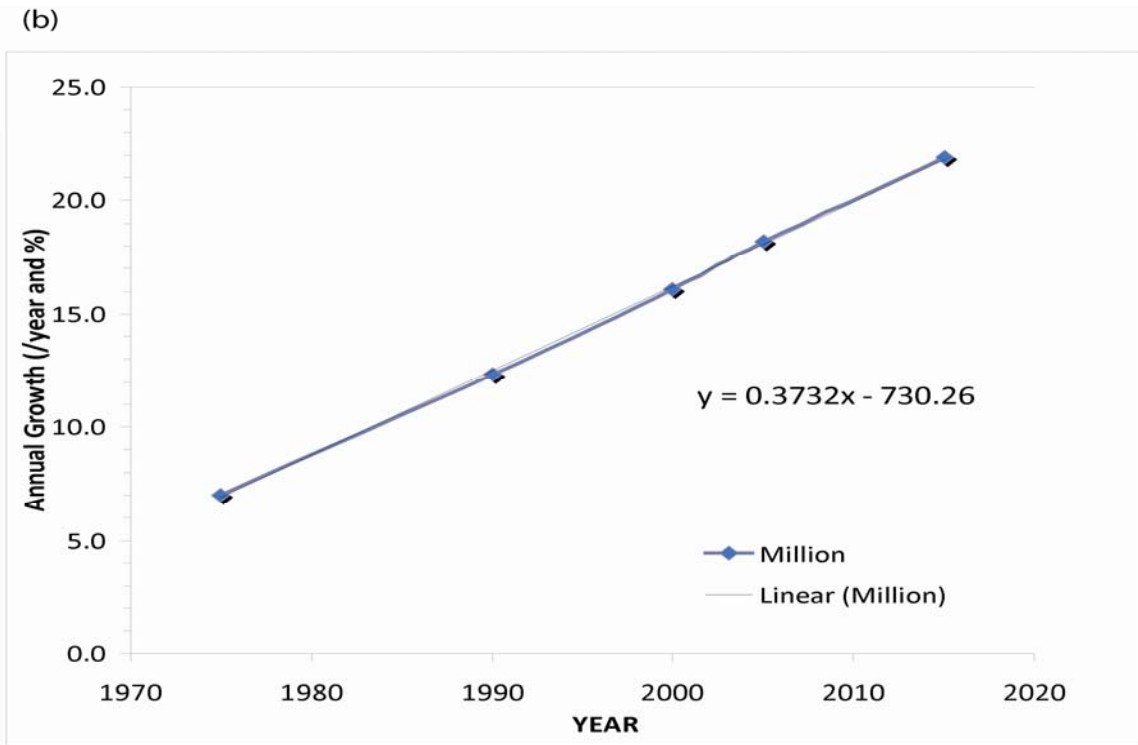


Figure 9b.

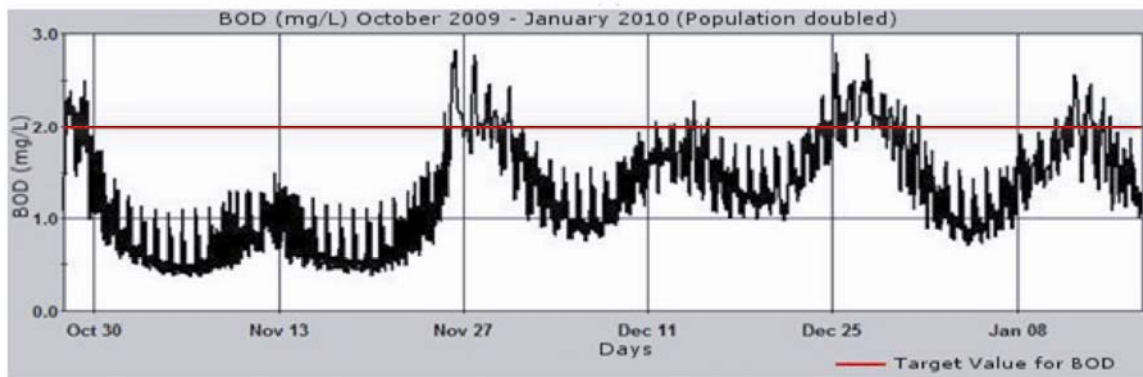


Figure 10.