Stagnant Surface Water Bodies (SSWBs) as an Alternative Water Resource for the Chittagong Metropolitan Area of Bangladesh: Physico-Chemical Characterization in terms of Water Quality Indices

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Abstract

The concern over ensuing fresh water scarcity has forced the developing countries to delve for alternative water resources. In this study we examined the potential of stagnant surface water bodies (SSWBs) as alternative fresh water resources in the densely populated Chittagong metropolitan area (CMPA) of Bangladesh – where there is an acute shortage of urban fresh water supply. Water samples, collected at one month intervals for a period of one year from 12 stations distributed over the whole metropolis. Samples were analyzed for pH, water temperature (WTemp), turbidity, electrical conductivity (EC), total dissolved solids, total solids, total hardness, dissolved oxygen (DO), chloride, orthophosphates, ammonia, total coliforms (TC) and trace metal (Cd, Cr, Cu, Pb, As and Fe) concentrations. Based on these parameters different types of water quality indices (WQIs) were deduced. WQIs showed most of CMPA-SSWBs as *good* or *medium* quality water bodies while none were categorized as *bad*. Moreover, it was observed that the minimal water quality index (WQI_m), computed using five parameters: WTemp, pH, DO, EC and turbidity gave reliable estimate of water quality. The WQI_m gave similar results in 72% of the cases compared with other WQIs which were based on larger set of parameters. Based on our finding, we suggest the wider use WQI_m in developing countries for assessing health of SSWBs as it will minimize the analytical cost to overcome the budget constraints involved in this kind of evaluations. It was observed that except turbidity and TC content, all other quality parameters fluctuated within the limit of World Health Organization suggested standards for drinking water. From our findings we concluded that if the turbidity and TC content of water from SSWBs in CMPA are taken care of, they will become good candidates as alternative water resources all round the year.

Keywords: surface water; water chemistry; water quality index; Chittagong; Urban water supply

1.0 Introduction

Water is inevitable for life on earth with its uses to meet our basic needs of drinking, cooking, washing, irrigation, farming etc. Fresh water, the water that is fit for human consumption, makes up 3% of the total water on earth; with over 68% of it being locked up in ice and glaciers, 30% being in the ground, we are left with a meager 0.3% of the total consumable water on earth for our consumption from different surface sources (Gleick 1993, 1996). For human consumption, we need *wholesome* water - water that is free from disease organisms, poisonous substances and excessive amounts of mineral and organic matter; and *palatable* water – water that is free from color, turbidity, taste and odor, and is well aerated (Ekpo & Inyang 2000, Fair et al. 1966).

Alike all developing countries, safe water is an important national issue for Bangladesh – a country with an approximate population density of 900/km^2. Two decades ago, for Bangladesh, surface water was the only fresh water source. But over this time, in liaison with its development partners, the country became successful in providing groundwater-based, microbial-free water supply through network of shallow and deep tube-wells. Even after the remarkable success with hand pumped and piped water, use of unsafe water is still in common parlance as manifested by the fact that water-related diseases remained the major cause of mortality in Bangladesh (Ahmed et al. 1998, Hoque et al. 2006). Moreover, the geogenic contamination of groundwater with high level of arsenic in Bangladesh has caused widespread human exposure to this toxic element (Karim 2000, Rahman et al. 2003, Rahman et al. 2008) which makes the search for alternative sources of safe water for the people of Bangladesh a sheer necessity.

Bangladesh, with an acre of water body for every eight persons, has one of the highest man-water ratios in the world. Surface water bodies *eg.* ponds and tanks, almost evenly distributed throughout the country, comprise 336000 acres which is about 10% of total inland water area (Khan 2000). These are the potential alternatives to arsenic contaminated underground water. However, processes like anthropogenic inputs of chemicals from industry, agriculture, urbanization etc along with natural causes like changes in climate, atmospheric inputs, weathering and erosion of crustal materials induce variations in the water chemistry and limit its uses for drinking, industrial, agricultural, recreation or other purposes (Lehr & Keeley 2005). A representative and substantial quality estimate of the surface water resources for arsenic laden Bangladesh is therefore necessary. This goal can be obtained through the regular investigation of water quality parameters and their spatial and temporal variations in response to anthropogenic and natural factors influencing the surface water systems. With this view, a GIS-based quality assessment of the open and stagnant surface water bodies (SSWBs) of Chittagong Metropolitan City Area (CMPA) was conducted. CMPA represents the second largest metropolis of Bangladesh with a geography that includes hills, plain lands, ponds, ditches, lakes and other water bodies (Osmany 2006). Statistical approaches were used to extract information about the spatial and temporal patterns of water quality within the sampling stations. The results were compared with the reference acceptable limits of the quality parameters.

Though the water quality standards are well defined for various singular purposes like preservation of aquatic life, water for recreational purpose, or water drinking or cleaning etc. (Chapman 1992, WHO 1987), an evaluation of overall water quality from a large number of samples in temporal and spatial contexts is challenging (Chapman 1992, Pesce & Wunderlin 2000). The use of water quality indices (WQI) is a common practice to circumvent the intrinsic difficulty of assessing overall quality standard involving a certain set of water bodies (Chapman 1992). Water quality indices are intended to provide a simple but reliable tool for managers and decision makers on the quality of water for a wide range of uses for a given set of water bodies (Bordalo et al. 2001). In this paper we report overall spatial and temporal quality verification of CMPA-SSWBs through construction of WQI from multiple physico-chemical parameters studied over a period of one year. We tried to come up with suggestions for a sustainable strategy for the preservation and utilization of these resources, and to explore their potentials as alternative water resource for urban residents in CMPA. Most of the parameters included in this study are recommended by the Global Environmental Monitoring System – United Nations Environmental Program (WHO 1987). Exploitation probability of SSWBs as an alternative water resource is also discussed based on the implications of findings of the study and those from the evaluation of water quality in developing countries.

2.0 Materials and Methods

2.1 Study area

2.1.1 Geographic location

Chittagong, the second largest metropolis of Bangladesh and the economic gateway of the country, is situated between 22°14´N and 22°24´30´´N and between 91°46´E and 91°53´E, on the right bank of the river Karnaphuli. Chittagong Metropolitan Area (CMPA) comprises of 41 Wards (individual administrative entities with urban and civic facilities) (Figure 1) occupying about 168 $km^2$of land area. The metropolis is inhabited by a sizable population of more than 2.5 million (BBS 2006a, BBS 2009).

2.1.2 Topography, geology and hydrological setting

Being a part of the hilly regions that branch off from the Himalayas, Chittagong has quite different topography from the rest of Bangladesh. The area is located on a narrow piedmont zone along the western base of the Chittagong Hills. The land slopes quite uniformly from east to west and is dissected by courses of generally parallel small streams from the base of the hills to the sea. Larger rivers that head further inland also traverse the plains several locations. Thus, the geographic environment of Chittagong city comprises hills, plain lands, ponds, ditches, lake and other water bodies. Parts of the area subject to tidal inundation twice in a day by the semi-diurnal tide originating from the Bay of Bengal, and are predominantly under the tidal influence throughout the year. The lands in the area have been formed by piedmont alluvial deposits transported from the Chittagong Hills by local streams and rivers, some land were formed by beach and tidal flat deposits. Soils in this area are generally younger and coarse textured, and consist primarily of fine sands, silts, silty sands, sand silts and clayey silts (Anonymous 1985, Osmany 2006).

2.1.3 Climate

The metropolis is greatly influenced by the seasonal monsoon. Mean annual rainfall is 2687 mm, mean annual temperature is 26.24°C. There are three distinct seasons, the pre-monsoon summer from March through May, the humid monsoon rainy season from June through October, and the cool dry winter from November through February. The summer is characterized by high temperature and occurrence of thunderstorms causing 10 to 25 percent of the annual total rainfall. The rainy season coincides with the summer monsoon is characterized by southerly or south-westerly winds, very high humidity, and long consecutive days of heavy rainfall giving 70 to 85 percent of annual precipitation. During the winter, the temperature remains low, cool air blows from the west or northwest, and the rainfall is scanty. Sunshine period is shorter during rainy and winter seasons and is longer in summer with an annual mean of about 5–6 hours per day (Ahmed & Mohanta 2006, Harun 2006).

2.1.4 Urban water supply scenario

In CMPA, Chittagong Water Supply and Sewerage Authority (CWASA) is the organization managing water supply by using treated water from the *Halda* river and 78 deep tube wells. About 0.4 million families in CMPA get water from house connection while about 0.2 million people use water from street hydrants. However, a large portion of Chittagong city's population still face severe water problem and collects water from natural fountains, private supplies and natural reservoirs such as ponds, canals and rainwater catchments (BBS 2006b, Hasna 1995, Khan 2006, Osmany 2006).

2.2 Inventory of stagnant surface water bodies (SSWBs)

There are several artificial lakes and ponds or *dighis*, as they are popularly known, in Chittagong Metropolitan City (CMPA) (Khan 2000, Osmany 2006). Inventory and assessment of Stagnant Surface Water Bodies (SSWBs) in CMPA for this study was based on data from social survey, field measurement, master plan of Chittagong Development Authority, Chittagong City Corporation administrative map (1:50,000 scale), topographic map (1:10,000 scale) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images. Spatial distribution of the open and stagnant natural surface water reservoirs of CMPA, as identified and described elsewhere (Hossain et al. 2009) in detail, with sampling locations are shown in Figure 2.

2.3 Collection, preservation and analysis of water samples

2.3.1 Sample collection

Surface water samples were collected from twelve different pre-selected locations of Chittagong Metropolitan Area (CMPA) on the first day of each month from July 2007 to June 2008. Surface area distribution of a certain water body, and its relative existence within the context of the study area were carefully considered during the selection of sampling sites. Sampling stations' are shown in Figure 2 in terms of their geo-point references, and brief information about the sampling stations is presented in Table 1.

2.3.2 Environmental variables

Water samples were analyzed for water temperature (WTemp), pH, electrical conductivity (EC), dissolved oxygen (DO), total dissolved solids (TDS), total solids (TS), total hardness (hardness), chloride (Cl^-), orthophosphates (as phosphorus, PO_4-P), ammonia (as nitrogen, NH_3-N), turbidity and total coliforms (TC). Collection, preservation and analyses of the samples were done in accordance with standard procedures (Clesceri et al. 1998) as listed in Table 2. Analytical grade chemicals from Merck (Darmstadt, Germany) and Sigma Aldrich (St.Louis, MO) were used without further purification to analyze the samples.

2.3.3 Trace metals

Water samples were assayed to determine the content of following trace metals: Cd, Cr, Cu, Pb, As and Fe. A Shimadzu AA-6800 atomic absorption/emission spectrometer also equipped with a graphite furnace atomizer and deuterium background correction was used for all metal measurements. The radiation sources were hollow cathode lamps (Shimadzu, Tokyo, Japan). The operating conditions were those recommended by the manufacturer (Anonymous 2000). Stock standard solutions of metals at a concentration of 1000 mg L^{-1} were obtained from Merck (Darmstadt, Germany). Standard methodology as described by Clesceri et al. (1998) were followed for the preservation and pre-treatment of the samples.

2.4 Water quality index

Water quality index (WQI) ascribes a quality value to an aggregate set of measured parameters reflect the collective influence of various physicochemical and biological criteria of water on its quality. It is a cumulatively derived numerical expression defining water quality (Miller et al. 1986). The construction of WQI involves a normalization step in which a 0–100 scale is set for each parameter with 100 representing the highest quality. After normalization, weighing factors are applied to reflect the relative importance of each parameter as an indicator of the water quality. Based on these two steps using the raw data, WQI is constructed which gives an easily comprehendible unitless number representing the quality percentage of the water resource under question (Jonnalagadda & Mhere 2001, Pesce & Wunderlin 2000, Sánchez et al. 2007, Stambuk-Giljanovic 1999). The WQI approach has many variations (Bordalo et al. 2001). In this work, to include maximum of the measured

CMPA-surface water quality variables for the classification of water, as reported in other studies (Kannel et al. 2007, Pesce & Wunderlin 2000, Sánchez et al. 2007), objective water quality index (WQI_{obj}) was used:

$$WQI_{obj} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \qquad (1)$$

Here, C_i is the normalized value and P_i is the relative weight assigned to each parameter. P_i ranges from 1 to 4, with 4 representing the maximum impact of a parameter (*e.g.*, dissolved oxygen) on the water quality for specific use. The water quality classification system adopted for this report is as follows- WQI 0–25 is very bad, >25–50 is bad, >50–70 is medium, >70–90 is good and >90–100 is excellent, as proposed by Jonnalagadda and Mhere (2001), Dojlido et al. (1994) and Kannel et al. (2007). Relative weights and normalization factors for different parameters that were used in the evaluation process are listed in Table 3, as adopted from Cude (2001), Pesce and Wunderlin (2000), Debels et al. (2005), Sánchez et al. (2007), Kannel et al. (2007).

Now, as the construction of WQI_{obj} requires measurement of many physical and chemical parameters, it is not a cost effective water quality assessments needed for developing countries with scarce budgets (Ongley & Booty 1999). Rather, the construction of WQI based on few simple parameters will be an advantage (Kannel et al. 2007, Ongley 1997). Under this scenario, minimum water quality index (WQI_{min}), as adopted from Pesce and Wunderlin (2000) and Kannel et al. (2007), was computed using five important parameters *i.e.* temperature, pH, DO, turbidity and electrical conductivity. Giving equal weights to each parameter, the minimum water quality index was calculated as:

$$WQI_{\min} = \frac{\sum_{i=1}^{5} C_i P_i}{5} \qquad (2)$$

However, to avoid the possible over-estimation, as observed by Pesce and Wunderlin (2000) and Kannel et al. (2007), another water quality classification system called minimal water quality index (WQI_m) was generated from the regression analysis between the results of WQI_{obj} and $WQI_{\min}$ as:

$$WQI_m = \alpha WQI_{\min} + \beta \tag{3}$$

Here, α and β are regression constants.

2.5 Analysis and integration of data

GIS (Geographical Information Systems) software used in this study was ArcView 3.2 (Environmental Systems Research Institute, Inc. Redlands, CA). ENVI 3.4 (Research Systems, Inc., Boulder, CO) was used for processing and analyzing geospatial imagery. MS Excel 2003 (Microsoft Corporation, Redmond, WA), SPSS Statistics 16.0 (SPSS, Inc., Chicago, IL) and DeltaGraph 5.6 (Red Rock Software, Inc., Salt Lake City, UT) were used for data processing and analysis.

3.0 Results and Discussion

3.1 Spatial distribution of stagnant surface water bodies (SSWBs)

In total, about 438 ha of SSWBs were identified from the satellite imagery of CMPA and the size distribution was shown in Figure 3. About 45.6%, 28.0%, 10.5%, 5.11%, 6.25% and 1.42% were in the size interval of <0.25 ha, 0.25 to <0.50 ha, 0.50 to <0.75 ha, 0.75 to <1.00 ha, 1.00 to <2.00 ha and 2.00 to <3.00 ha, respectively. The average size of SSWBs was 0.62 ha and the largest of them occupied 43.0 ha. Larger numbers of SSWBs were located in South Pothenga, North Pothenga, South Halishahar, South Middle Halishahar, North Middle Halishahar, North Halishahar, South Kattali and North Kattali wards while no SSWBs were identified in West Madarbari, Firingee Bazar, Enayet Bazar, Dewan Bazar, Bagmoniram, Lal Khan Bazar and Pahartali wards (Figure 1 and Figure 2).

3.2 Water quality assessment of SSWBs

3.2.1 Environmental variables

Descriptive statistics of the water quality variables featuring seasonal dynamics are summarized in Table 4. Figure 4 illustrates averaged spatial dynamics of selected variables for different sampling stations.

Temperature of surface water bodies varied between 28.2 and 30.6°C. The seasonal variation in the water temperature was not significant which may be due to the tropical weather condition and less rainfall during the study period as observed also in Thailand (Bordalo et al. 2001). Water pH is an important indicator of the chemical condition of the environment. In the present study, at different SSWBs the pH ranged from 7.98 to 8.12 over different seasons. Low annual variation in free CO_2, increase of which decreases pH, can be considered responsible for narrow annual fluctuation in pH (Avvannavar & Shrihari 2008).

Seasonally averaged turbidity and electrical conductivity values ranged from 10.5 to 10.9 NTU and 210 to 270 $\mu s\ cm^{-1}$ respectively. Presence of decaying organic matter could be attributed as the cause of the turbidity level (Rim-Rukeh et al. 2007) while the conductivity of water corresponds to the highest concentrations of dominant ions, which is the result of ion exchange and solubilization in the aquifer (Virkutyte & Sillanpää 2006). The DO level in the water samples ranged from 3.53 to 4.87 mg L^{-1}. Mixing of oxygen demanding organic wastes coupled with high temperature might have resulted in the depletion of DO (Avvannavar & Shrihari 2008). Carbonates and bicarbonates of calcium and magnesium cause hardness. Expressed in terms of calcium carbonate, water with less than 50 mg L^{-1} total hardness is 'soft' and water with more than 100 mg L^{-1} is 'hard' (Ekpo & Inyang 2000). The values of t-hardness in our samples ranged between 39.3 and 65.5 mg L^{-1} which might be attributed to the rainwater intrusion, dissolution of soil minerals and rocks (Al-Khashman 2008). Total solids and total dissolved solids contents in the water samples ranged between 238 to 302 and

104 to 135 mg L^{-1} which may be due to the anthropogenic activities and addition of sewage at nonpoint sources (Avvannavar & Shrihari 2008).

Chloride, PO_4-P, and NH_3-N are among the major components responsible for the alteration of water quality. The ranges of chloride, PO_4-P, and NH_3-N in the CMPA-SSWBs were 22.3 to 28.8, 0.26 to 0.36 and 0.01 to 0.05 mg L^{-1}, respectively. These might have originated from domestic effluents, fertilizers and from natural sources such as rainfall, dissolution of fluid inclusions, and Cl^- bearing minerals (Al-Khashman 2008, Jeong 2001, Ritzi et al. 1993).

Total coliform count (TC) at different seasons of a year, and averaged value at different sampling stations are presented in Table 4 and Figure 4 respectively. Higher TC values in CMPA-SSWBs may be due to high temperature and climatic conditions in the study area as observed for the spring water of Shoubak area, Jordan (Al-Khashman 2008). Negligible waste water feed during the rainy season from anthropogenic activities could be a reason for the non-significant seasonal variation (Al-Kharabsheh & Ta'any 2003).

3.2.2 Trace metals

Sources of trace metals present in natural water are associated with either natural processes or human activities. Chemical weathering and soil leaching are the two important natural sources contributing to the increase in trace metals' concentrations in water (Drever 1988). Factors that affect the release of trace metals from primary materials and soil, and consequently their stability are pH, adsorption characteristics, hydration, and co-precipitation etc. (Drever 1988, Fetter 2001).

Cumulative seasonal variations in trace metal contents of CMPA-SSWBs are given in Table 5 and averaged content at different sampling points are illustrated in Figure 5. Ranges of concentrations of cadmium, chromium, copper and lead were 0.064 to 0.216, 0.162 to 0.167, 0.229 to 0.260 and 0.203 to 0.224 μg mL^{-1}, respectively. Low metallic content was observed for most of the water samples which can be attributed to the high pH value (>7.5) which may have enhanced the deposition of these metals or have restricted their dissolution from the soil matrix (Al-Awadi et al. 2003). However, the total iron content was high and ranged from 1.004 to 1.761 mg L^{-1}. Water samples were also analyzed for total arsenic content considering the observation of Yokota et al. (2001) for the surface water of Samta, Bangladesh and it was below the detectable limit.

3.2.3 Water quality indices

Though some partial analyses are possible and contribution from the pollution sources can be predicted, it is not easy to evaluate the overall variation of the water quality by analyzing separate parameters due to the discrete pattern in the seasonal and spatial variation of the environmental variables (Pesce & Wunderlin 2000). Water quality index (WQI) is a relevant and reliable indicator to evaluate the changes in water quality due to the combined effect of many parameters (Chapman 1992).

Three different water quality indices *i.e.* objective water quality index (WQI_{obj}), minimum water quality index (WQI_{min}) and minimal water quality index (WQI_m) were constructed for the quality evaluation of CMPA-SSWBs water. However, considering the possibility of overestimation by WQI_{min} approach, WQI_{obj} and WQI_m have been used in this study for the overall water quality classification and assessment.

Seasonal dynamics and comparative water quality classifications for different sampling stations of CMPA-SSWBs with the water quality indices are summarized in Table 6. Water quality variation was not distinctly varied among the seasons; though, in general, the overall water quality was better in the rainy-monsoon season.

Spatial annual average of water quality indices were used to construct a plot (Figure 6) which showed a maximum WQI value for S4 (74.9, WQI_{obj}; 74.1, WQI_m) and the minimum was for S7 (57.2, WQI_{obj}; 60.2, WQI_m). WQI obtained for S7 (57.2, WQI_{obj}; 60.2,

WQI_m) was the lowest among all the sampling stations, which was situated in the most densely populated area (population density: 2.11×10^5/mile^2) of the CMPA. However, sampling station S2 which was classified as a water body of '*medium'* quality is located in the area with the lowest population density (1.57×10^4/mile^2) indicating that population density or urbanization can only be used as an added tool to describe the water quality of a certain water body in conjunction with other related factors. The WQI analysis, considering both WQI_{obj} and WQI_m, enabled us to classify S1, S3, S4, S11 and S12 of CMPA-SSWBs as *good* and the others are as of *medium* quality. None of the sampling stations in CMPA-SSWBs was *bad* as water resource.

When we compared the indexing approaches used in this study using table 6 and figure 6, we could see that WQI_{min} or WQI_m which were based on five parameters *i.e.* temperature, pH, DO, turbidity and electrical conductivity gave comparable results to the WQI_{obj} which was based on all the twelve parameters measured. Out of all the cases, in 72% of the cases both the indices gave the same quality class for the water bodies concerned. In 11% of the cases, WQI_{obj} categorized particular water bodies (e.g. S2, S10) as of *medium* quality while WQI_{min} or WQI_m indices indicated them *good* and in the rest 17% of the cases, WQI_{obj} indicated *good* quality while WQI_{min} or WQI_m indices indicated *medium* for particular waterbodies (*e.g.* S1, S4, S5 etc.). Since the indexing approaches agreed in majority of the cases and differed marginally only while categorizing between *good* and *medium*, we can suggest that WQI_m can alone be used for such categorization purpose which will minimize the cost and time needed for such studies thereby helping developing countries to undertake such investigations within the limit of their budget constraints.

3.3 Analysis of the CMPA-SSWBs for drinking purpose

A comparison of the selected physico-chemical and biological characteristics of the analyzed water samples was made with the WHO drinking water standards to explore their suitability for drinking purpose (Table 7). Parameters considered in this comparison were pH, DO, turbidity, TDS and TC. From the comparison, we concluded that CMPA-surface water is feasible for drinking all the year round in terms of pH, DO and TDS content. But, if turbidity and microorganisms content is considered, treatment of the surface water is required to meet the quality standards and such treatments are not so difficult or costly.

4.0 Conclusion

Investigation of physical, chemical, and biological properties of stagnant surface water bodies (SSWBs) at Chittagong Metropolitan Area (CMPA) of Bangladesh were carried out on a monthly basis over a period of one-year with a view evaluate the potential of these water bodies as alternative water resources for urban water supply. The study was based primarily on the construction of WQI using the water quality parameters for the assessment of water health of these sources. We observed temporal and spatial variations in water quality parameters which indicated the influence of natural and anthropogenic factors on the water quality.

WQI produced a classification of SSWBs based on their water quality from which we could get indication about the level of water pollution in these sources. WQI_{obj} (based on twelve parameters), WQI_{m}, WQI_{min} (based on five parameters - temperature, pH, DO, turbidity and EC) were investigated. None of the CMPA-SSWBs was classified '*bad*', and most of them were classified as '*medium*' based on WQIs. The indices WQI_{min}, WQI_{m}, in general, showed similarity with WQI_{obj} with slight overestimation of the water quality in case of WQI_{min}. However, WQI_{m} formulated using only five factors showed almost the same estimation of water quality as WQI_{obj}. This is a significant finding in the sense that we can suggest the developing countries to use this index to assess water resources with minimum time and analytical cost.

Biologically, the SSWBs in the Chittagong metropolitan area were polluted and concentration of total coliforms was high enough to make the raw water unpalatable. Turbidity is another factor that is to be addressed to make water from these resources usable. Trace metal concentrations in the water from SSWBs were within the limits outlined by WHO standards for drinking water. The best thing was that none of the water bodies were contaminated with arsenic which is a major issue against the use of ground water in Bangladesh. These observations made us to suggest that SSWBs are suitable as an alternate source of water supply in Chittagong metropolitan area. But we need further research to investigate the specific natural or anthropogenic factors contributing to turbidity or coliform problems and means to mitigate them. Moreover, we need investigation to find out exactly how much water supply can be sustained from these resources without jeopardizing their very existence. At the same time efforts to create reliable WQIs based on smaller number of easily measurable parameters should continue.

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Tables

Table 1: Information about the sampling stations

Sampling station	Local name of the sampling station	Corresponding ward (sub-administrative entities) Information				
		Ward No.	Ward Name	Area (mile^2)	Population (thousands)	Population Density (number/mile^2)
S1	Fateabad dighi	1	South Pahartali	4.14	96.1	2.32×10^4
S2	Olima dighi	2	Jalalabad	5.23	82.3	1.57×10^4
S3	Bahaddar bari pond	6	East Sholashahar	0.94	38.5	4.10×10^4
S4	Foy’s lake	9	North Pahartali	2.12	70.7	3.33×10^4
S5	Biswas para dighi	10	North Kattali	1.09	44.9	4.13×10^4
S6	Jora dighi	12	Saraipara	1.03	80.4	7.81×10^4
S7	Askhar dighi	21	Jamal Khan	0.29	61.3	2.11×10^5
S8	Agrabad deba	28	Pathantooli	0.47	70.2	1.50×10^5
S9	Laldighi	32	Anderkilla	0.41	76.7	1.87×10^5
S10	Dopar dighi	37	North Middle Halishahar	1.45	69.0	4.74×10^4
S11	Chairman pond	40	North Pothenga	3.70	94.4	2.55×10^4
S12	Chor para pond	41	South Pothenga	3.90	64.3	1.65×10^4

Table 2: Water quality parameters, units and analytical methods used for CMPA-surface water evaluation

Parameter	Units	Analytical methods	Instruments
Water temperature	°C	Instrumental, Analyzed *in situ*.	Combo meter, Model HI 98129 (HANNA Instruments, Inc., Woonsocket, RI)
pH	-	Instrumental, Analyzed *in situ*.	Combo meter, Model HI 98129 (HANNA Instruments, Inc., Woonsocket, RI)
Electrical conductivity	μS cm^{-1}	Instrumental, Analyzed *in situ*.	Combo meter, Model HI 98129 (HANNA Instruments, Inc., Woonsocket, RI)
Dissolved oxygen	mg L^{-1}	Membrane Electrode Method, Analyzed *in situ*.	Jenway DO Meter, Model 970 (Bibby Scientific Limited, Staffordshire, UK)
Total dissolved solids	mg L^{-1}	Instrumental, Analyzed *in situ*.	Combo meter, Model HI 98129 (HANNA Instruments, Inc., Woonsocket, RI)
Total solids	mg L^{-1}	Filtration and gravimetric method	Temperature controlled oven (WTB Binder, Tuttlingen, Germany)
Total Hardness	mg L^{-1}	Titrimetric method	Titration assembly
Chloride	mg L^{-1}	Argentometric method	Titration assembly
Orthophosphates (as phosphorus)	mg L^{-1}	Vanadomolybdophosphoric acid/Ascorbic acid colorimetric method	Direct reading spectrophotometer, Model DR 2000 (HACH Company, Loveland, CO)
Ammonia (as nitrogen)	mg L^{-1}	Nesslerization method	Direct reading spectrophotometer, Model DR 2000 (HACH Company, Loveland, CO)
Turbidity	NTU	Nephelometric method	Nephelometer, Lovibond TM 750 (The Tintometer Ltd., Amesbury, UK)
Total coliforms (TC)	MPN·100 ml^{-1}	Multiple-tube fermentation technique	–

Table 3: Variables used in the water quality index calculation, scores of normalization and relative weights

Variable	Relative weight (p_i)	Normalization factor (C_i)										
		100	90	80	70	60	50	40	30	20	10	0
WTemp	1	21/16	22/15	24/14	26/12	28/10	30/5	32/0	36/-2	40/-4	45/-6	>45/<-6
pH	1	7	7–8	7–8.5	7–9	6.5–7	6–9.5	5–10	4–11	3–12	2–13	1–14
EC	1	<750	<1000	<1250	<1500	<2000	<2500	<3000	<5000	<8000	≤12000	>12000
DO	4	≥7.5	>7	>6.5	>6	>5	>4	>3.5	>3	>2	≥1	<1
TDS	2	<100	<500	<750	<1000	<1500	<2000	<3000	<5000	<10000	≤20000	>20000
TS	4	<250	<750	<1000	<1500	<2000	<3000	<5000	<8000	<12000	≤20000	>20000
T-Hardness	1	<25	<100	<200	<300	<400	<500	<600	<800	<1000	≤1500	>1500
Cl^-	1	<25	<50	<100	<150	<200	<300	<500	<700	<1000	≤1500	>1500
PO_4-P	1	<0.025	<0.05	<0.1	<0.2	<0.3	<0.5	<0.75	<1	<1.5	≤2	>2
NH_3-N	3	<0.01	<0.05	<0.1	<0.2	<0.3	<0.4	<0.5	<0.75	<1	≤1.25	>1.25
Turbidity	2	<5	<10	<15	<20	<25	<30	<40	<60	<80	≤100	>1003
TC	3	<50	<500	<1000	<2000	<3000	<4000	<5000	<7000	<10000	≤14000	>14000

Table 4: Cumulative descriptive statistics for environmental variables in CMPA-SSWBs: seasonal dynamics

Parameter	Units	Season[a]	Mean[b]	SD[c]	Min.	Max.
WTemp	°C	Hot Pre-monsoon	28.7	0.2	28.5	28.8
		Rainy-monsoon	30.6	1.3	28.9	31.8
		Dry-winter	28.2	0.4	27.7	28.6
pH	pH units	Hot Pre-monsoon	7.98	0.14	7.86	8.14
		Rainy-monsoon	8.11	0.23	7.76	8.34
		Dry-winter	8.12	0.01	8.11	8.13
EC	µS cm^{-1}	Hot Pre-monsoon	270	21	252	293
		Rainy-monsoon	210	20	184	238
		Dry-winter	227	37	192	270
DO	mg L^{-1}	Hot Pre-monsoon	3.75	0.27	3.52	4.05
		Rainy-monsoon	4.87	1.26	3.34	6.30
		Dry-winter	3.53	0.27	3.18	3.83
TDS	mg L^{-1}	Hot Pre-monsoon	135	10	126	146
		Rainy-monsoon	104	10	92	119
		Dry-winter	113	19	96	135
TS	mg L^{-1}	Hot Pre-monsoon	302	32	267	331
		Rainy-monsoon	269	57	215	352
		Dry-winter	238	17	221	257
T-Hardness	mg L^{-1}	Hot Pre-monsoon	63.9	39.2	20.0	95.4
		Rainy-monsoon	39.3	10.3	25.9	50.4
		Dry-winter	65.5	52.5	21.5	141.4
Chloride	mg L^{-1}	Hot Pre-monsoon	28.8	0.3	28.5	29.2
		Rainy-monsoon	22.3	4.0	18.7	28.3
		Dry-winter	23.0	3.5	19.6	27.0
PO_4-P	mg L^{-1}	Hot Pre-monsoon	0.33	0.08	0.26	0.42
		Rainy-monsoon	0.26	0.07	0.19	0.38
		Dry-winter	0.36	0.03	0.33	0.40
NH_3-N	mg L^{-1}	Hot Pre-monsoon	0.05	0.01	0.04	0.06
		Rainy-monsoon	0.04	0.04	0.00	0.08
		Dry-winter	0.01	0.02	0.00	0.03
Turbidity	NTU	Hot Pre-monsoon	10.5	2.1	8.7	12.8
		Rainy-monsoon	10.8	3.9	7.3	17.5
		Dry-winter	10.9	1.1	9.9	12.2
Total Coliforms (TC)	MPN·100 ml^{-1}	Hot Pre-monsoon	8.3E+04	2.0E+04	6.6E+04	1.0E+05
		Rainy-monsoon	2.4E+05	2.0E+05	2.9E+04	5.0E+05
		Dry-winter	1.8E+05	9.7E+04	1.2E+05	3.3E+05

[a] Hot pre-monsoon season (March–May), rainy-monsoon season (June–October), and dry-winter season (November–February)

[b] Values are averaged from at least three consecutive measurements.

[c] Standard deviation

Table 5: Cumulative descriptive statistics for trace metal content in CMPA-SSWBs: seasonal dynamics

Parameter	Units	Season[a]	Mean[b]	SD[c]	Min.	Max.
Arsenic (As)	$\mu g\ L^{-1}$	Hot Pre-monsoon	--	--	--	--
		Rainy-monsoon	--	--	--	--
		Dry-winter	--	--	--	--
Cadmium (Cd)	$\mu g\ L^{-1}$	Hot Pre-monsoon	0.12	0.07	0.09	0.34
		Rainy-monsoon	0.22	0.13	0.16	0.63
		Dry-winter	0.06	0.04	0.05	0.19
Chromium (Cr)	$\mu g\ L^{-1}$	Hot Pre-monsoon	0.17	0.03	0.09	0.19
		Rainy-monsoon	0.17	0.02	0.13	0.20
		Dry-winter	0.16	0.05	0.00	0.20
Copper (Cu)	$\mu g\ L^{-1}$	Hot Pre-monsoon	0.23	0.04	0.15	0.34
		Rainy-monsoon	0.23	0.05	0.07	0.26
		Dry-winter	0.26	0.07	0.23	0.47
Lead (Pb)	$\mu g\ L^{-1}$	Hot Pre-monsoon	0.20	0.00	0.20	0.21
		Rainy-monsoon	0.22	0.01	0.21	0.24
		Dry-winter	0.20	0.01	0.19	0.21
Iron (Fe)	$mg\ L^{-1}$	Hot Pre-monsoon	1.3	0.3	1.0	1.6
		Rainy-monsoon	1.0	0.7	0.3	2.1
		Dry-winter	1.8	0.1	1.7	1.9

[a] Hot pre-monsoon season (March–May), rainy-monsoon season (June–October), and dry-winter season (November–February)

[b] ‘-’, Below detectable limit. Values are averaged from at least three consecutive measurements.

[c] Standard deviation

Table 6: Water quality classification for different sampling stations in CMPA-SSWBs using the water quality indices: comparison

Sampling stations	Season[a]	WQI	Water class	WQI_{min}	WQI_{m}	Water class
S1	Hot Pre-monsoon	73.3	Good	76.0	73.1	Good
	Rainy-monsoon	73.8	Good	74.0	70.1	Medium
	Dry-winter	75.8	Good	78.0	76.0	Good
S2	Hot Pre-monsoon	68.3	Medium	76.0	73.1	Good
	Rainy-monsoon	69.2	Medium	70.0	64.1	Medium
	Dry-winter	69.2	Medium	74.0	73.1	Good
S3	Hot Pre-monsoon	66.7	Medium	72.0	67.1	Medium
	Rainy-monsoon	73.8	Good	78.0	76.0	Good
	Dry-winter	67.5	Medium	74.0	70.1	Medium
S4	Hot Pre-monsoon	73.3	Good	76.0	73.1	Good
	Rainy-monsoon	75.8	Good	80.0	79.0	Good
	Dry-winter	75.4	Good	74.0	70.1	Medium
S5	Hot Pre-monsoon	66.3	Medium	70.0	64.1	Medium
	Rainy-monsoon	72.9	Good	74.0	70.1	Medium
	Dry-winter	65.8	Medium	66.0	58.2	Medium
S6	Hot Pre-monsoon	67.1	Medium	74.0	70.1	Medium
	Rainy-monsoon	73.3	Good	74.0	70.1	Medium
	Dry-winter	69.2	Medium	70.0	64.1	Medium
S7	Hot Pre-monsoon	56.3	Medium	68.0	61.2	Medium
	Rainy-monsoon	55.8	Medium	64.0	55.2	Medium
	Dry-winter	59.6	Medium	70.0	64.1	Medium
S8	Hot Pre-monsoon	65.0	Medium	72.0	67.1	Medium
	Rainy-monsoon	71.3	Good	76.0	73.1	Good
	Dry-winter	69.2	Medium	74.0	70.1	Medium
S9	Hot Pre-monsoon	68.8	Medium	72.0	67.1	Medium
	Rainy-monsoon	70.4	Good	74.0	70.1	Medium
	Dry-winter	70.4	Good	72.0	67.1	Medium
S10	Hot Pre-monsoon	67.9	Medium	76.0	73.1	Good
	Rainy-monsoon	71.7	Good	76.0	73.1	Good
	Dry-winter	65.8	Medium	66.0	58.2	Medium
S11	Hot Pre-monsoon	69.6	Medium	76.0	73.1	Good
	Rainy-monsoon	67.5	Medium	74.0	70.1	Medium
	Dry-winter	67.1	Medium	74.0	70.1	Medium
S12	Hot Pre-monsoon	72.5	Good	76.0	73.1	Good
	Rainy-monsoon	74.6	Good	76.0	73.1	Good
	Dry-winter	73.3	Good	76.0	73.1	Good

[a] Hot pre-monsoon season (March–May), rainy-monsoon season (June–October), and dry-winter season (November–February)

Table 7: Results of selected water quality parameters of CMPA-SSWBs as compared to World Health Organization (WHO) guideline values for drinking water

Parameter	Units	Standards[a]	Mean±SD[b]	Range	Suitability[c]
pH	pH units	6.5 – 8.5	8.07±0.08	7.91 – 8.20	S
DO	mg L^{-1}	4 – 6	4.05±0.72	3.35 – 4.73	S
Turbidity	NTU	5	10.7±0.21	8.63 –14.2	NS
TDS	mg L^{-1}	500	117±15.9	105 – 133	S
Total Coliforms (TC)	MPN·100 ml^{-1}	50	$1.7\times10^5\pm7.9\times10^4$	7.2×10^4 – 3.1×10^5	NS

[a] WHO suggested water quality standards (Gray 2008, WHO 2004)

[b] Values are averaged from at least three consecutive measurements. SD: standard deviation

[c] Suitability for drinking as compared with WHO suggested water quality standards. 'S', suitable; 'NS', not-suitable.

Figures

Figure 1: Wards of Chittagong Metropolitan City. Name of the 41 wards:

01.	South Pahartali	11.	South Kattali	21.	Jamal Khan	31.	Alkaran
02.	Jalalabad	12.	Saraipara	22.	Enayet Bazar	32.	Anderkilla
03	Panchlaish	13.	Pahartali	23.	North Pathantooli	33.	Firingee Bazar
04	Chandgaon	14.	Lal Khan Bazar	24.	North Agrabad	34.	Patharghata
05.	Mohra	15.	Bagmoniram	25.	Rampur	35.	Boxir Hat
06.	East Sholashahar	16.	Chawk Bazar	26.	North Halishahar	36.	Gosaildanga
07.	West Sholashahar	17.	West Bakalia	27.	South Agrabad	37.	North Middle Halishahar
08.	Sulakbahar	18.	East Bakalia	28.	Pathantooli	38.	South Middle Halishahar
09.	North Pahartali	19.	South Bakalia	29.	West Madarbari	39.	South Halishahar
10.	North Kattali	20.	Dewan Bazar	30.	East Madarbari	40.	North Pothenga
						41.	South Pothenga

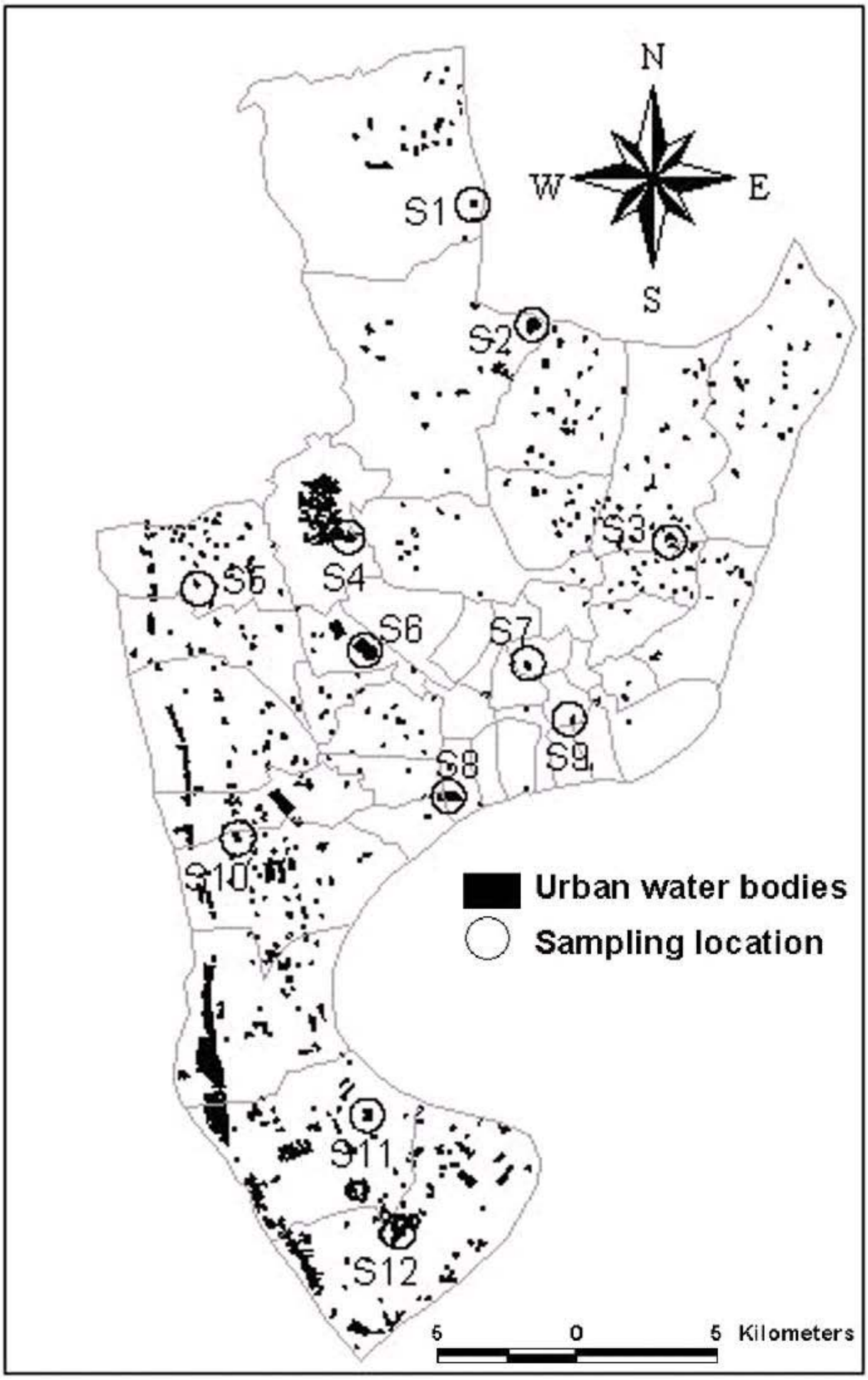

Figure 2: Urban water bodies of Chittagong Metropolitan Area (classification of ASTER satellite image) with sampling locations.

S1.	Fateabad dighi	S5.	Biswas para dighi	S9.	Laldighi
S2.	Olima dighi	S6.	Jora dighi	S10.	Dopar dighi
S3.	Bahaddar bari pond	S7.	Askhar dighi	S11.	Chairman pond
S4.	Foy’s lake	S8.	Agrabad deba	S12.	Chor para pond

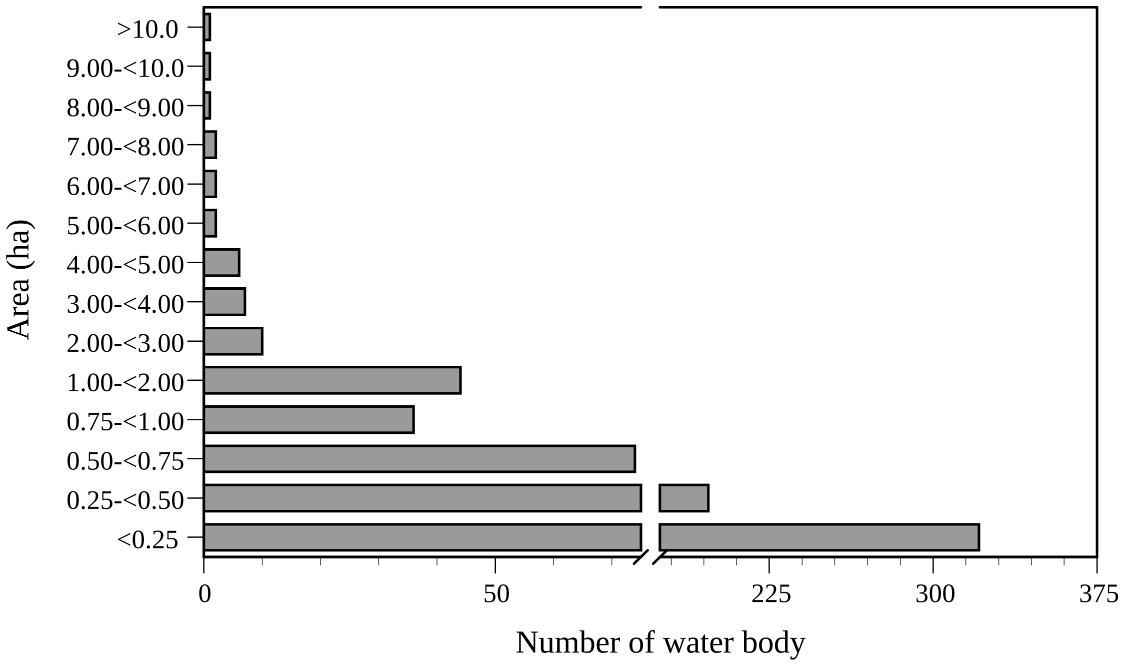

Figure 3: Surface area distribution of stagnant surface water bodies (SSWBs) based on the satellite image interpretation.

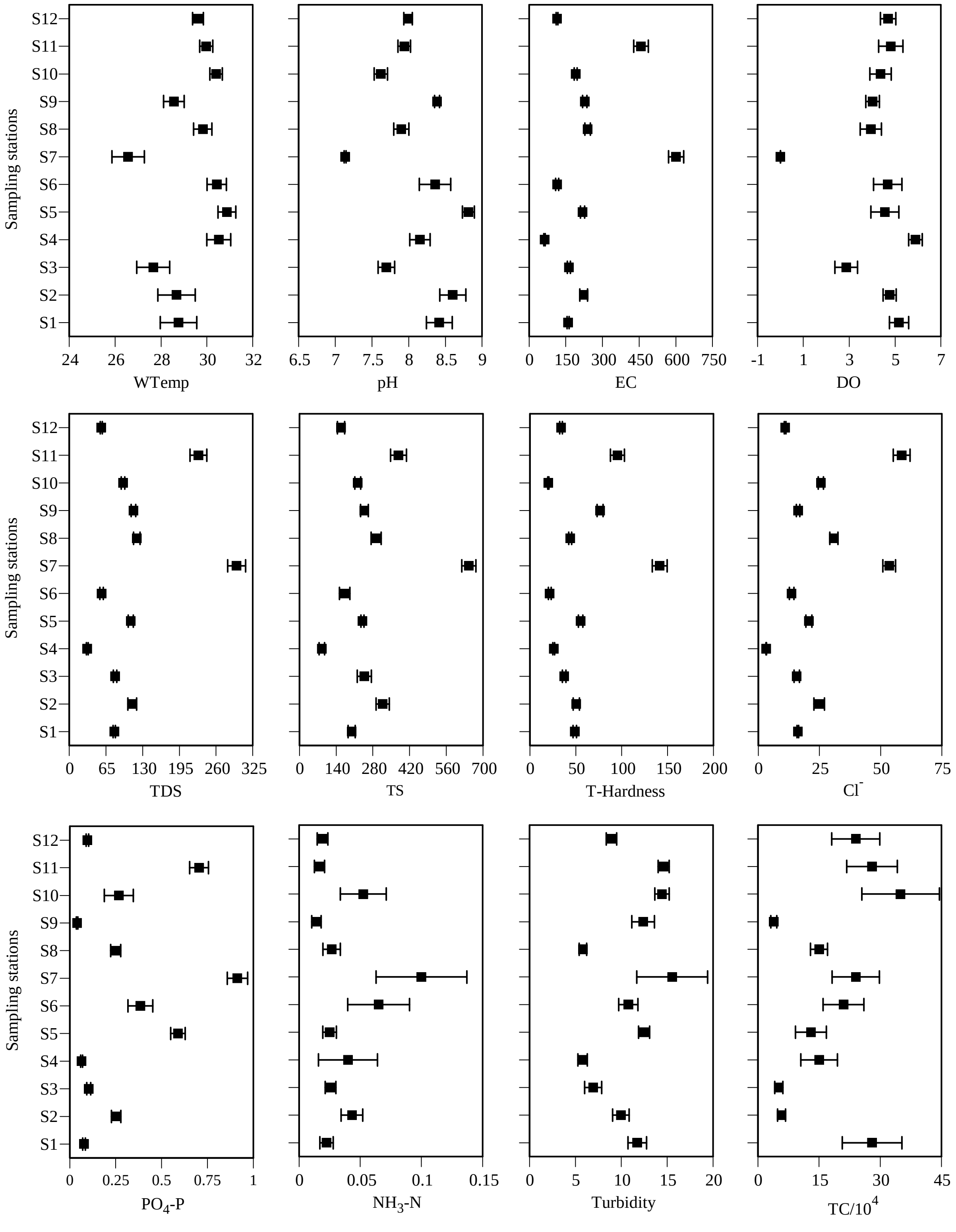

Fig. 4 Spatial dynamics of environmental variables (annual mean values ± standard error [SE]; n = 36) in CMPA-SSWBs (concentration units in milligrams per liter excluding those mentioned; WTemp in degrees Celsius, pH in pH units, EC in microsiemens per centimeter, turbidity in nephelometric turbidity units, and TC in MPN·100 mL^{-1}).

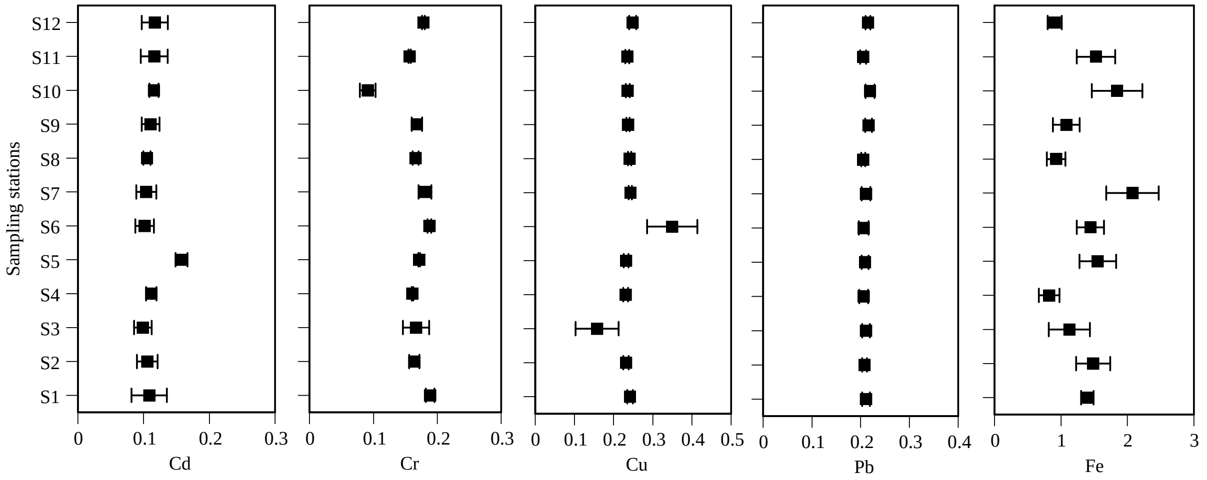

Figure 5: Spatial dynamics of trace metal contents (annual mean values±SE) (n=36) in CMPA-SSWBs. (concentration units in μg L^{-1} for Cd, Cr, Cu and Pb, Fe in mg L^{-1}).

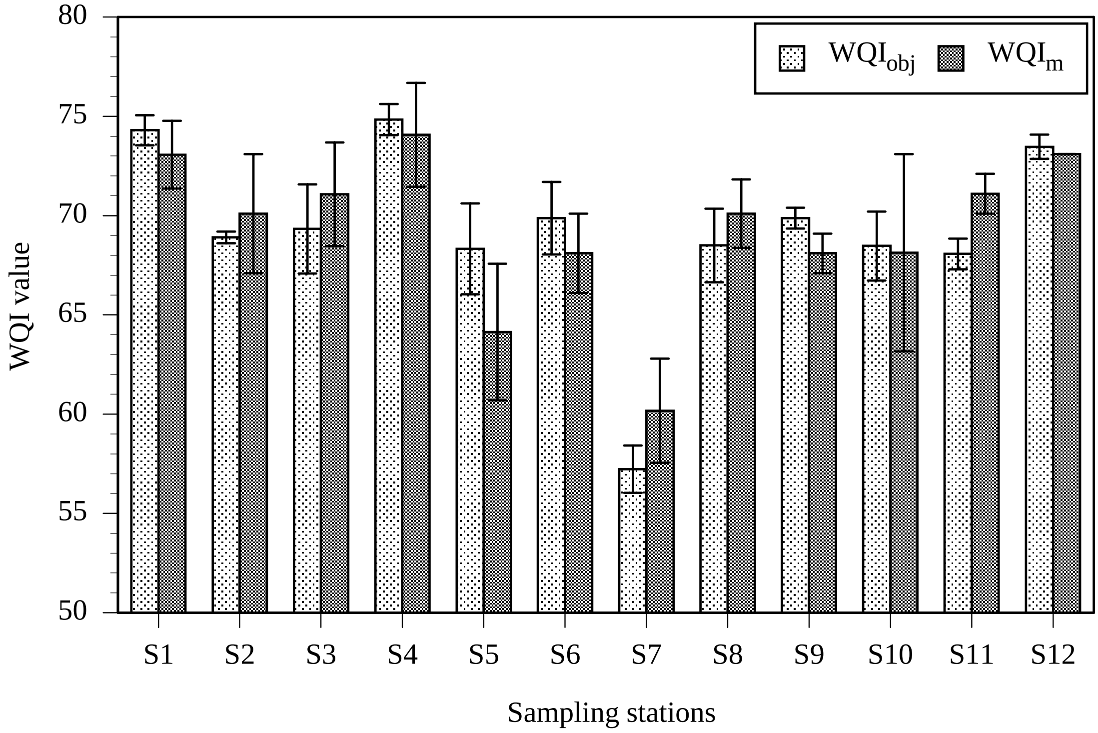

Figure 6: Spatial averaged water quality indices±SE for stagnant surface water bodies (SSWBs) in CMPA