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Spatial Patterns and Temporal Trends in the Water Quality of the Tuul River in Mongolia

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Abstract

The purpose of this research is to assess spatio-temporal variability of water quality determinands of the Tuul River in surrounding area of Ulaanbaatar city, Mongolia using an extensive dataset between 1998 and 2008. It presents the spatio-temporal assessment and seasonal pattern of 14 hydro-chemical determinants at 15 monitoring sites in the study area. According to the Mongolian water quality classification system, all sections of the Tuul River and its tributaries in the surrounding area of Ulaanbaatar city belong to moderately and heavily polluted waters due to high concentration of ammonium. In accordance with European Union water quality standard, the downstream section of the Tuul River fails. In order to change this situation, operation enhancement of wastewater treatment plants and artificial increment of dissolved oxygen concentration become crucial to improve the water quality significantly. Perhaps a new wastewatertreatment plant is needed for Ulaanbaatar city.

Keywords: Tuul River, water quality, pollution source, dissolved oxygen, water quality map, Mongolia

1. Introduction

Unpolluted waters in rivers are a vital natural resource, providing drinking and irrigation water for humans, livestock and agriculture. However, water quality in many large river waters has deteriorated significantly worldwide due to anthropogenic activities in the past two-three decades (Ferrier et al., 2001). It is also widely accepted that discharges from sewage treatment plants provide major fluxes of P and N to rivers, predominantly in populated urban areas (Jarvie, Neal, & Withers, 2006; Neal et al., 2005). Nutrient enrichment can result in excessive growth of aquatic plants and reductions in dissolved oxygen (Neal et al., 2002; Whitehead, Johnes, & Butterfield, 2002).

Rising pollution levels and the increasing demand for water and the associated increased discharges of pollutants are having significant impacts on the water cycle and water quality (Whitehead, Wilby, Battarbee, Kerman, & Wade, 2009; Whitehead, Wilby, Butterfield, & Wade, 2006). Climate change is also starting to have some effects with increasing temperatures and changed rainfall patterns. The increasing air temperatures and decreasing river flows in warmer months are the main concerns, and intensive water use is often constrained by the lack of natural low flow, and low flow rivers are more affected by effluent discharges from cities, industries, and agriculture (Johnes, 2007; Mainstone & Parr, 2002).Surface waters in Mongolia have tended to decrease in recent years due to the combined effect caused by the decrease of precipitation and the increase of potential evaporation as a result of rising air temperature. This situation indicates that droughts may occur more frequently due to the effects of global warming (Sato, Kimura, & Kitoh, 2007).

Over the last decade, rapid urbanization and increased industry have had significant impacts on the water quality and chemical composition of rivers in the surrounding area of Ulaanbaatar city (Javzan, Sauleguli, & Tsengelmaa, 2004). Air and soil pollution as well as accumulated wastes in the catchment area, are being transferred by surface runoff and flood events into the local river systems and having a significant impact on the river water quality. Major causes of the water pollutants are mining industries in the lower basin of the Tuul

River. More than 180 licensed mining companies are operating in 145 km^2 areas of the basin (MNE, 2006). Water demand of the city had increased by 20% from 1998 to 2005. Population growth, urbanization and intensity of industries have created water exploitation, deterioration of natural water regime and ecological degradation of the Tuul River basin (Roza-Butler, 2004).The treatment efficiency of the CWTP as well as other Wastewater Treatment Plants (WTP) in the region is often inadequate due to technical and financial problems. Efficiency of the CWTP was 71% in 2002. This value dropped to 66% in 2003. The plant was not operated in May 2003 and April 2004 (Orchlon, 1995).

For that reason, this study hascarried out a spatio-temporal water quality research of the Tuul River in surrounding area of Ulaanbaatar city, Mongolia in order to assess the recent state of water quality and sources of pollution.This paper presents the comprehensive analysis of chemical data of water qualityin the Tuul River and identifies spatio-temporal patterns in water quality from 1998 to 2008.The aims of this research are i) to assess spatio-temporal variability of water quality determinands and nutrients of the Tuul River and its tributaries; ii) to evaluate the overall state of water quality and explore its implications and iii) to produce most recent water quality maps of the river using Mongolian water quality classification andEU standards insurrounding area of Ulaanbaatar city.

2. Study Area, Data and Method

2.1 Study Area

The study was carried out in surrounding area of Ulaanbaatar (UB); the capital of Mongolia and population of the city is approximately one million. The Tuul River, flowing through the heart of the Ulaanbaatar city, is an environmentally, economically and socially significant natural resource. The study area covered the Tuul River and its three tributaries, namely Terelj, Uliastai, Selbe Rivers and discharge from CWTP. List of sampling points and their geographical locationsare shown in Table 1 and Figure 1.The point sources of pollution in the Tuul River are poorly treated waste water treatment plants at Nalaikh (1400 m^3 day^{-1}), Nisekh (400 m^3 day^{-1}), CWTP (190000 m^3 day^{-1}), Bio-industry (490 m^3 day^{-1}) and Bio-Songino (600 m^3 day^{-1}). The biggest point source is CWTP, which is located in the western edge of Ulaanbaatar city (Orchlon, 1995).

As shown in Figure 1, there are five point sources of pollution (some may overlap in the figure) marked by triangles and 15 dots indicated the water quality monitoring sites. Pink lines represented the inflows into the main river, a blue line shown the Tuul River and polygon features symbolized territory of the city and settling areas, respectively.

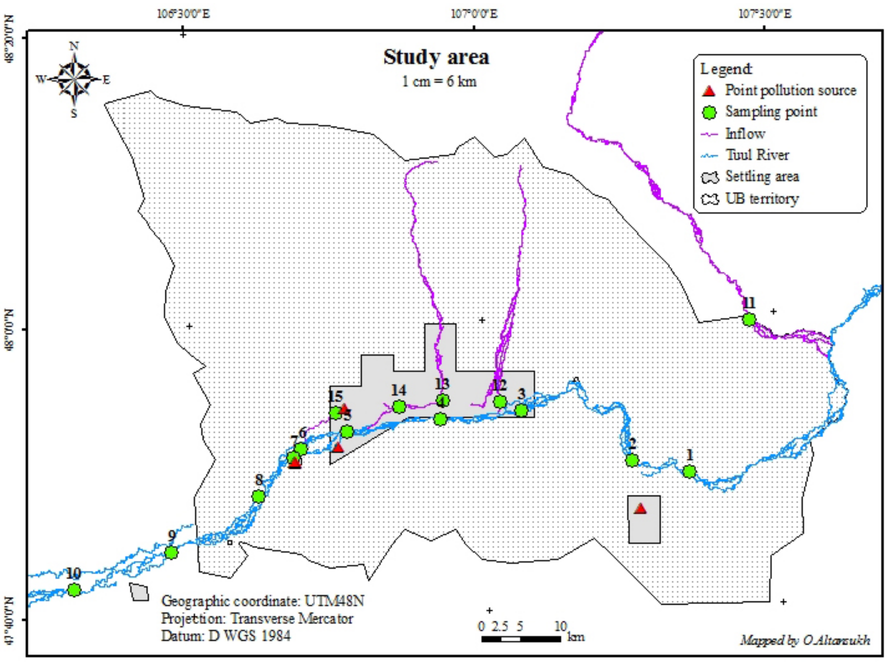

Figure 1. Study area

The river pertains to 6^{th} order of the Strahler river classification system. In the territory of Ulaanbaatar city, there are about 50 streams and rivers. Three of them, named Selbe, Uliastai and Tuul, flow through the central part of the capital (Altansukh, 2008). Annual runoff of the Tuul River consists of three components namely rainfall (69%), groundwater flow (26%) and snowmelt (5%) based on an analysis by Basandorj and Davaa (Basandorj & Davaa, 2006). The average channel width of the river is 35 to 75 m during a low flow period, the depth is 0.8-3.5 m and the velocity is 0.5-1.5 ms^{-1}.The long-term annual mean flow of the river is approximately 26.6 m^3 s^{-1}. The observed maximum discharge has reached 1580 m^3s^{-1} and 564 m^3s^{-1} at the Ulaanbaatar and the Terelj stations, respectively. During the low flow period of the warm season, the recorded minimum flow has fallen to 1.86 m^3s^{-1} at the Ulaanbaatar station and 0.44 m^3s^{-1} at the Terelj station (NAMHEM, 1999).

Characteristics of the catchment area have been estimated by digital elevation model based on hydro-processing using Shuttle Radar Topography Mission data with 90 m resolution. The Tuul River catchment is one of twenty-nine basins in Mongolia (Figure 2a). It is situated in central part of the country and bounded by $108^0$18’E-$48^0$30’N, $105^0$22’E-$46^0$22’N, $102^0$47’E-$47^0$50’N and $104^0$47’E-$48^0$56’N, roughly. The catchment area is 57560.4 km^2, which covers 3.67% of the entire territory of Mongolia. The perimeter of the catchment area is 1998.5 km, and the drainage density is 103.63 m km^{-2}. The length of the Tuul River is 826.4 km and the elevations of riverhead and the river outlet are 2272.0 m and 776.0 m, respectively. Therefore, the river slope is 1.81 m km^{-1} and flows from the northeast to north. The headwaters of the river and most of the tributaries originate in the mountainous area that forms northeast part of the catchment (Figure 2b).

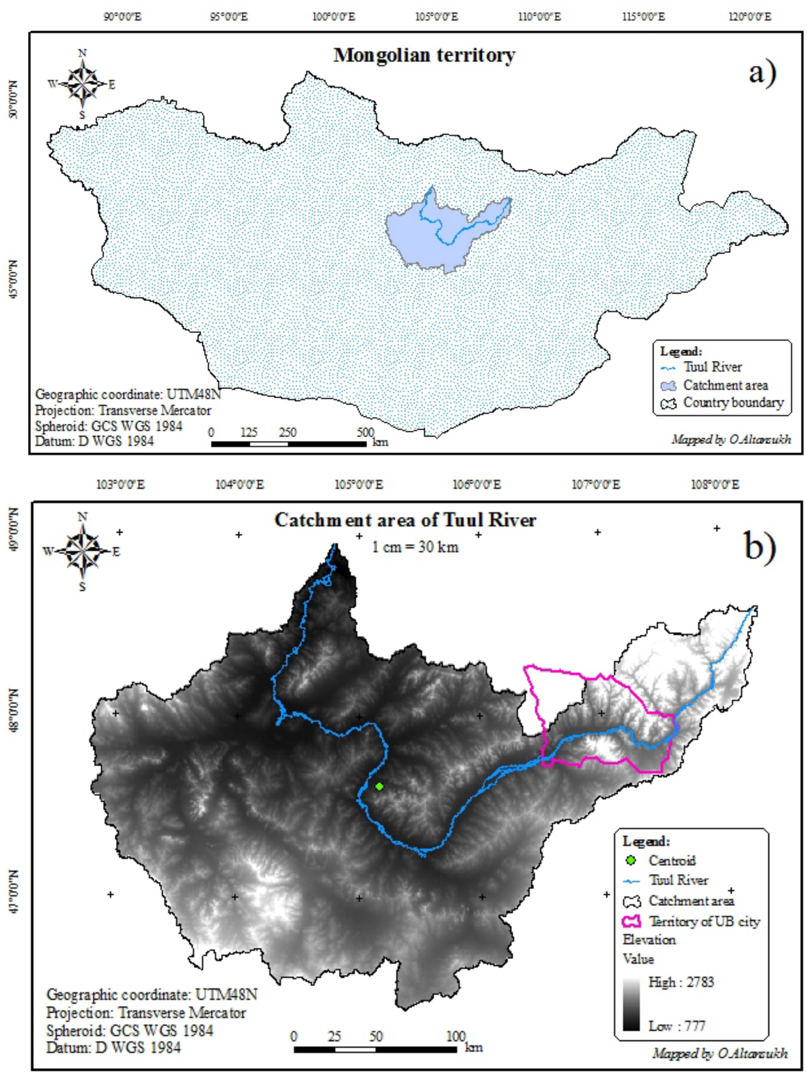

Figure 2. Maps of a) The Tuul River catchment in Mongolian territory and b) The catchment area, including the Tuul River and the study area, UB city

The Tuul River basin has the continental climatic features that are characterized by wide variation of annual, monthly and daily temperatures; low range of air humidity; non-uniform distribution of precipitation; cold and long-lasting winter and warm summer. The rainy period continues from June to August in the upper Tuul River basin, of which rainfall shares about 74% of the annual precipitation (MNE, 1997a). The annual average air temperature is -1.2^{0}C in the study area. Annual minimum temperature reaches -39.6^{0}C in January,while maximum temperature reaches +34.5^{0}C during summer period (Basandorj & Davaa, 2006).

The Tuul River quality is naturally clean and rich in calcium bicarbonate. Total dissolved solid of the river water ranges from 100-210 mg l^{-1}, pH= 6.1-7.5 along its reaches. The river contains 28.1 mg l^{-1} mineral, and it belongs to the bicarbonate class, calcium group. The main cationis calcium, and dominant anion is bicarbonate. Moreover, cation proportion is Ca^{+2}> Mg^{+2}> (Na^++K^+) and the anion ratio is HCO_3^-> SO_4^{-2}>Cl^-. Naturally, anion and cation proportionas well as chemical content of the water matches with the pure water of river (NAMHEM, 1999). However, chemical contents of the river suddenly change from the western part of the city. The main factor of the chemical changes is the incompletely treated waste water from the CWTP that is pouring into the Tuul River (Altansukh, 2005). According to the results of a hydrological survey conductedin 2003, the hydrological regime and its runoff formation zones of the Tuul River are gradually being changed and polluted by the settlements, intensive overgrazing, timbering, wild fires and improper waste water treatment in the river banks (Basandorj & Davaa, 2006).

2.2 Chemical Dataset

Surface water quality in the surrounding area of Ulaanbaatar is being monitored at 14 points by 30 determinands in every month since 1980s. For this purpose, 10 sampling points along the Tuul River and 4 points attributaries of the Tuul River (1 at Terelj River, 1 at Uliastai River, 2 at Selbe River), were chosen by the Central Laboratory of Environmental Monitoring (CLEM). Stationary hydro-biological monitoring of invertebrate species along the river has started since 1997 (MNE, 2006).

Thus in this study, we focused on more recent datasets from 1998-2008, total 11 years, at those 14 sites. Additionally, we included chemical monitoring dataset of CWTP discharge for evaluation of the treatment plant effect (Figure 1 and Table 1). In total, 1980 samples were taken at 15 sampling points along the Tuul River and its inflows (tributaries + the CWTP discharge) and analysed by CLEM and the laboratory of CWTP. Water quality determinands presented in this paper are dissolved oxygen (DO), biological oxygen demand (BOD_5), ammonium (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N), phosphate (PO_4^{-3}) as well as major dissolved ions, such as calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^+) sulphate(SO_4^{-2}), chloride (Cl^-), bicarbonate (HCO_3^-) and others, totally 15 variables.

Table 1. Spatial and temporal information of water quality sampling

ID	Name of sites	Latitude N	Longitude E	Altitude m	Distance km	Temporal sampling	Selection
			Monitoring sites along the Tuul River				
1	Tuul – Uubulan	47°49'11"	107°21'02"	1383	0	monthly	Base load
2	Tuul – Nalaikh	47°49'56"	107°15'07"	1364	11	monthly	Nalaikh WTS impact
3	Tuul – Bayanzurkh	47°53'34"	107°03'53"	1309	28	monthly	Inflow to the city
4	Tuul – Zaisan	47°53'13"	106°55'36"	1293	12	monthly	Centre of the city
5	Tuul – Sonsgolon	47°52'26"	106°46'21"	1272	13	monthly	Outflow from the city
6	Tuul – Songino (upper)	47°51'17"	106°41'22"	1256	9	monthly	Upper reach of CWTP
7	Tuul – Songino (down)	47°50'50"	106°40'28"	1254	2	monthly	Lower reach of CWTP
8	Tuul – Chicken farm	47°48'13"	106°36'46"	1233	10	monthly	Self-purification
9	Tuul – Khadankhyasaa	47°44'23"	106°27'35"	1217	21	monthly	Self-purification
10	Tuul – Altanbulag	47°41'54"	106°17'40"	1182	19	monthly	Self-purification
			Main inflows into the Tuul River				
11	Terelj - Terelj	47°59'30"	107°27'35"	1522	…	monthly	Tributary of the river
12	Uliastai - UB	47°54'07"	107°01'51"	1310	…	monthly	Tributary of the river
13	Selbe - UB	47°54'30"	106°55'55"	1290	…	monthly	Tributary of the river
14	Selbe - Dund	47°54'11"	106°51'23"	1276	…	monthly	Tributary of the river
15	CWTP - outflow	47°53'49"	106°44'56"	…	…	daily	Strongest impact

2.3 Analysis and Quality Classification

In this research, water quality classification, which developed by the Water Sector of the Ministry of Nature and Environment (MNE) in 1997 was used to classify the water quality. For the surface water quality classification, mean values of water variables were calculated from 2004-2008 datasets (Table 6). For general view of spatial data analysis, all chemical variables were averaged over the entire study period (Table 3). Using the time-series of chemicals, trend analysis has been applied to determine whether concentrations have increased or decreased during the time period for temporal assessment (Table 5). Furthermore, average quarterly data from 1998-2008 have been calculated in order to reveal seasonal variability (Figure 8). Inter-determinand relationships of mean hydro-chemicals have been assessed using the Pearson correlation technique and the results of relationship are shown in Table 4. The relationships between average general chemical concentrations are shown in the correlation matrix plots (Figure 3). ArcGIS 9.3 software was used for the mapping.

The annual means of water quality datasets for the Tuul River and its inflows have been compared to both Mongolian water quality classification system (WQCS) and EU water standards, so that the river water quality grades can be assessed (Figure 9). In total, 53 variables have been included inthe Mongolian WQCS (MNE, 1997b). However, the 15 variables of interest in this study are shown in Table 2. According to Mongolian legislation, the classification of surface waters with respect to their quality is given below as five classes, namely: class 1: very clean, class 2: clean, class 3: slightly polluted; class 4: moderately polluted; class 5: heavily polluted water. In Table 2, threshold values of Mongolian classification and EU standard are shown.

Table 2. The Mongolian water quality classification and the EU water standard

№	Parameters	Mongolian classification						EU standard
		Unit	Very clean 1	Clean 2	Slightly polluted 3	Moderately polluted 4	Heavily polluted 5	
1	pH	H^+	6.5-8.0	6.5-8.5	6.0-8.5	6.0-9.0	5.5-9.5	6.5-9.5
2	Suspended solid (SS)	mg l^{-1}	<=10.0	10.1-20.0	20.1-50.0	50.1-100.0	100.1=<	n.m
3	Dissolved oxygen (DO)	mg l^{-1}	>=9.0	8.9-8.0	7.9-6.0	5.9-4.0	3.9=>	n.m
4	Biological oxygen demand (BOD_5)	mg l^{-1}	<=3.0	3.1-5.0	5.1-10.0	10.1-15.0	15.1=<	n.m
5	Calcium (Ca^{+2})	mg l^{-1}	<=45.0	45.1-90.0	90.1-150.0	150.1-200.0	200.1=<	n.m
6	Magnesium (Mg^{+2})	mg l^{-1}	<=15.0	15.1-30.0	30.1-50.0	50.1-100.0	100.1=<	n.m
7	Sodium (Na^+)	mg l^{-1}			n.m			<=200
8	Potassium (K^+)				n.m			n.m
9	Sulphate (SO^{-2}_4)	mg l^{-1}	<=50.0	50.1-100.0	100.1-200.0	200.1-300.0	300.1=<	<=250
10	Chloride (Cl^-)	mg l^{-1}	<=50.0	50.1-150.0	150.1-250.0	250.1-350.0	350.1=<	<=250
11	Bicarbonate (HCO_3^-)				n.m			n.m
12	Ammonium (NH^+_4)	mg l^{-1}	<=0.020	0.021-0.050	0.051-0.100	0.101-0.300	0.301=<	<=0.5
13	Nitrite (NO^-_2)	mg l^{-1}	<=0.002	0.002-0.005	0.006-0.020	0.021-0.050	0.051=<	<=0.5
14	Nitrate (NO^-_3)	mg l^{-1}	<=1.0	1.1-3.0	3.1-5.0	5.1-10.0	10.1=<	<=50
15	Phosphorus (PO^{-3}_4)	mg l^{-1}	<=0.020	0.021-0.050	0.051-0.100	0.101-0.500	0.501=<	n.m

Source: EU, 1998; MNE, 1997b

In order to determine the classification, theaverage water quality for each applicable parameter has been determined at all sampling sites using the data from 2004-2008 to reveal the most recent water quality status. Then data has been compared to the five classes and the EU standard. The highest classhas been chosen to each site and two categories of "pass" and "fail" were given when assessing water quality using the EU standard.

3. Results

3.1 Summary of Average Hydro-chemical Variables

A statistical summary of hydro-chemical variable concentrations from 1998-2008 is shown in Table 3. A minimum of three years data are required to calculate average values for each site, which are used to calculate the proportion of major anion and cation charges by percent (Table 3).

Table 3. Summary of variables from 1998-2008 for each monitoring site

ID	pH	SS mg l^{-1}	DO mg l^{-1}	BOD_5 mg l^{-1}	Ca^{+2} mg l^{-1}	Mg^{+2} mg l^{-1}	$Na^{+}+K^{+}$ mg l^{-1}	SO_4^{-2} mg l^{-1}	Cl^{-} mg l^{-1}	HCO_3^{-} mg l^{-1}	NH_4^{+} mg l^{-1}	NO_2^{-} mg l^{-1}	NO_3^{-} mg l^{-1}	PO_4^{-3} mg l^{-1}
1	7.29	7.33	8.57	1.79	11.68	1.78	5.41	5.67	2.75	41.39	0.11	0.004	0.27	0.01
2	7.36	10.47	8.91	2.09	8.15	1.65	4.22	5.34	2.58	31.47	0.33	0.008	0.33	0.02
3	7.41	15.21	9.32	2.26	12.62	3.07	2.87	4.92	1.33	37.02	0.20	0.011	0.24	0.01
4	7.63	9.01	9.28	1.93	9.49	1.74	3.07	4.02	2.39	35.18	0.15	0.010	0.20	0.01
5	7.46	21.11	9.24	1.96	11.51	2.04	12.05	5.44	3.08	50.15	0.13	0.009	0.35	0.01
6	7.46	14.35	9.32	2.27	12.19	2.19	5.10	8.23	3.82	42.87	0.21	0.011	0.38	0.01
7	7.53	44.48	6.87	15.79	27.48	4.26	36.44	39.19	30.55	93.17	6.47	0.144	0.62	0.50
8	7.63	41.90	7.64	11.61	25.01	4.99	25.74	34.44	25.16	79.39	5.32	0.188	0.89	0.41
9	7.67	28.54	7.71	6.35	24.81	6.34	19.08	30.93	20.15	83.92	3.24	0.220	0.92	0.26
10	7.73	26.78	8.41	5.54	23.23	4.91	16.59	27.13	18.98	69.28	2.01	0.125	0.92	0.20
11	7.29	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	0.21	0.003	0.21	0.02
12	7.58	11.42	9.07	1.98	17.43	2.98	4.08	3.70	2.37	47.84	0.27	0.003	0.15	0.01
13	8.08	30.86	9.40	2.89	30.41	5.13	8.00	24.62	11.28	117.29	0.31	0.022	1.77	0.02
14	8.12	19.19	9.12	3.15	28.39	5.65	8.13	12.58	8.29	104.02	0.38	0.021	1.45	0.07
Excluded:														
15	8.00	35.58	4.56	27.67	n.a	n.a	n.a	45.01	54.33	n.a	15.37	0.219	4.84	2.28
Summary:														
Mean	7.59	21.59	8.68	4.59	18.65	3.60	11.60	15.86	10.21	64.08	1.38	0.056	0.62	0.11
Std	0.26	12.20	0.81	4.37	8.08	1.68	10.26	13.29	10.10	28.84	2.12	0.078	0.51	0.17
Min	7.29	7.33	6.87	1.79	8.15	1.65	2.87	3.70	1.33	31.47	0.11	0.003	0.15	0.01
Max	8.12	44.48	9.40	15.79	30.41	6.34	36.44	39.19	30.55	117.29	6.47	0.220	1.77	0.50
Proportion of major anion and cation charges, %					58.16	18.49	23.35	19.79	17.26	62.94				

Table 1 and Figure 1 show that the first 10 sampling points are on the Tuul River, and last 5 are on inflows to the river. As mentioned above, monitoring site 15 is excluded from calculations. Values of pH range from 7.29-8.12 with an average of 7.59±0.26, which falls within the normal range of river waters. Suspended solids (SS) have a broader range of values from 7.3 to 44.5 mg l^{-1} with a mean of 21.6±12.2mg l^{-1} (n=14). Calcium is the dominant cation; bicarbonate is the main anion.

The amount of Ca^{+2}, Mg^{+2} and HCO_3^{-} in the rivers as well as their 1:2 stoichiometric ratio linear relationship suggests that there is an overload of CO_2 with respect to the levels of calcium and magnesium, probably associated with anthropogenic sources such as coal burning for heating and cooking (Figure 3a). There are many other causes of air pollutionin the capital of Mongolia besides those more traditional sources (Guttikunda, 2007). A bi-variate plot of Na^{+} plus K^{+} versus Cl^{-} falls on 1:1 stoichiometric ratio line suggesting that waters in the river are mostly controlled by natural weathering (Figure 3b).

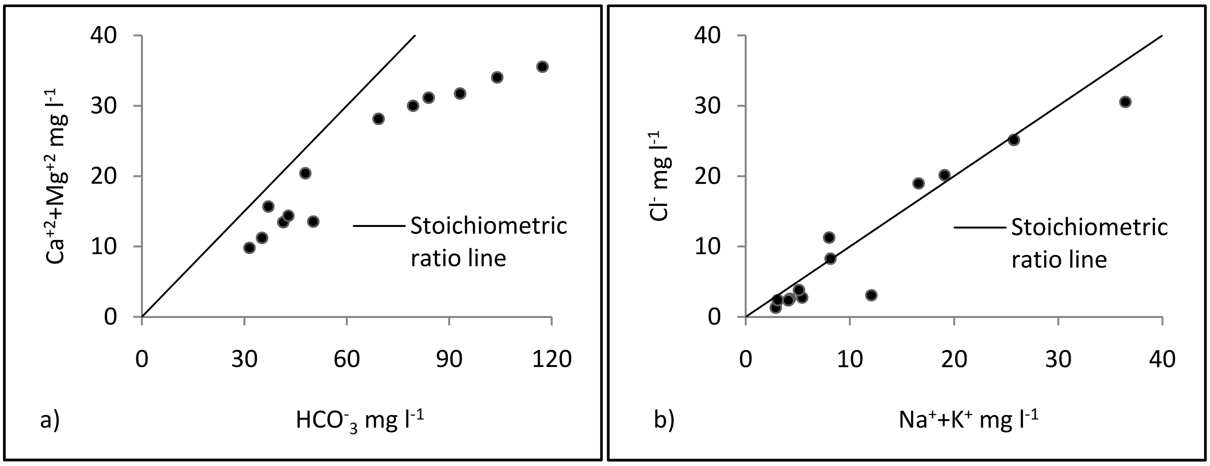

Figure 3. Bi-variate plots a) Ca^{+2}, Mg^{+2} versus HCO_3^-; b) Na^+, K^+ versus Cl^-

Oxygen parameters (DO, BOD_5) and nutrient concentrations (NH^{4+}, NO^{2-}, NO^{3-} and PO_4^{-3}), which depend on point and non-point pollution sources, are also variable across the study area. DO ranges from 6.87-9.40 with a mean of 8.68±0.81mg l^{-1}; BOD_5 values range from 1.8-15.8mg $l^{-1}$with a mean of 4.6±4.4mg l^{-1}. The mean concentrations of nutrients across the area are different. For instance, concentration of ammonium varies from 0.11-6.5 mg l^{-1} with an average of 1.38±2.12 mg l^{-1}; concentrations of ammonium are stable up to sampling point 7 when there is a sudden increase to 6.47 mg l^{-1}, followed by a gradual decrease along the Tuul River. The general pattern of phosphorus concentration is similar to that of ammonium. NO_2^- concentrations range between 0.003 and 0.22 mg l^{-1} with an average of 0.056±0.078 mg l^{-1}; nitrate and nitrite are stable up to point 7 when after a sudden increment intensive nitrification takes place along the Tuul River.

3.2 Spatial Pattern of Hydro-chemicals

3.2.1 General Chemical Variables

Threshold values are presented on the maps as five equal divisions between maximum and minimum values. Table 3 and Figure 4 show that the mean values of several monitoring sites have been omitted due to a lack of hydro-chemical analysis. A sixth threshold value has been obtained from the CWTP.

The spatial distribution of average values for general chemicals from 1998 to 2008 along the river is given in Figure 4. Major anions and cations display a similar spatial pattern in the study area with lower concentrations in the upper section of the river increasing downstream (Figure 4 a-f). The highest pH values are observed in the settlement area due to a strong anthropogenic influence. The concentration of SS varies with lower concentrations in the upper section of the river and highest concentration at the 7th sampling point (Figure 4b). Along the Tuul River, concentrations of Ca^{+2} plus Mg^{+2} and Na^+ plus K^+ remain steady at the first six monitoring sites but then rapidly increases at point number 7, caused by CWTP discharge. From this point, there is a gradual decrease to point 10 due to dilution (Figure 4c-d). Sulphate, phosphorus and bicarbonate have similar patterns as mentioned above (Figure 4e-f).

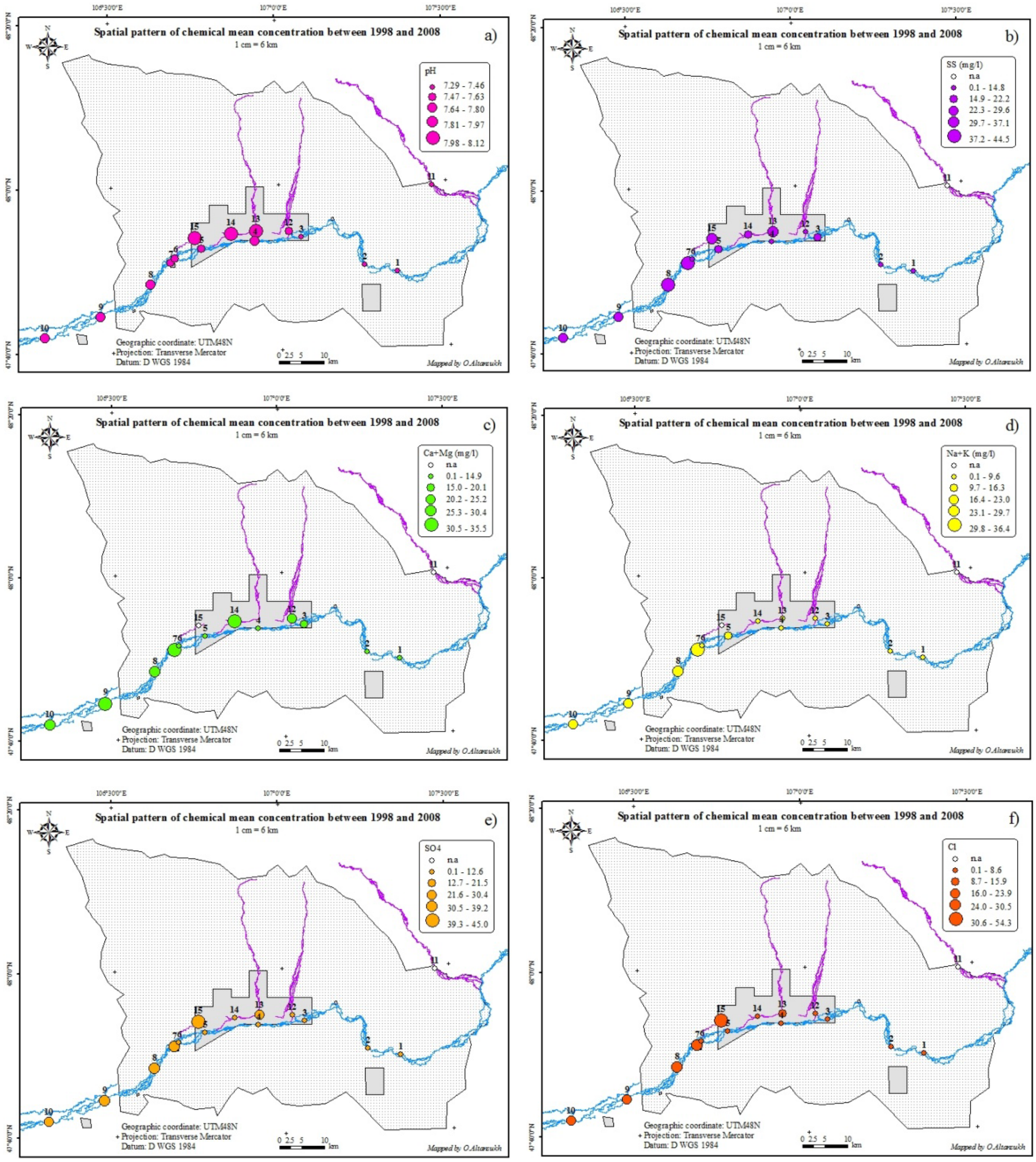

Figure 4. Spatial patterns of general hydro-chemicals between 1998 and 2008

3.2.2 Oxygen Parameters

The spatial distribution of average BOD_5 and DO values from 1998-2008 within the study area are presented in Figure 5. In the case of BOD_5, concentrations are generally low in the upper reaches of the river. However, downstream from the city of Ulaanbaatar, where CWTP discharge contaminates the water, BOD_5levels are elevated.Along the lower reaches of the river, concentrations gradually decrease (Figure 5b). Compared to other parameters, DO shows an inverse pattern, reflecting the natural re-aeration of the water, where chemical and biological reactions such as the oxidation and nitrification process have an effect (Figure 5a). There is one site in the Tuul River with a low DO concentration, which is normally associated with the year round discharge from a treatment plant. The waste water from that plant contains a high amount of nutrients and other chemical substances and can cause major reductions of DO. This would definitely kill aquatic fauna and ecology in the stretch of the river system affected.

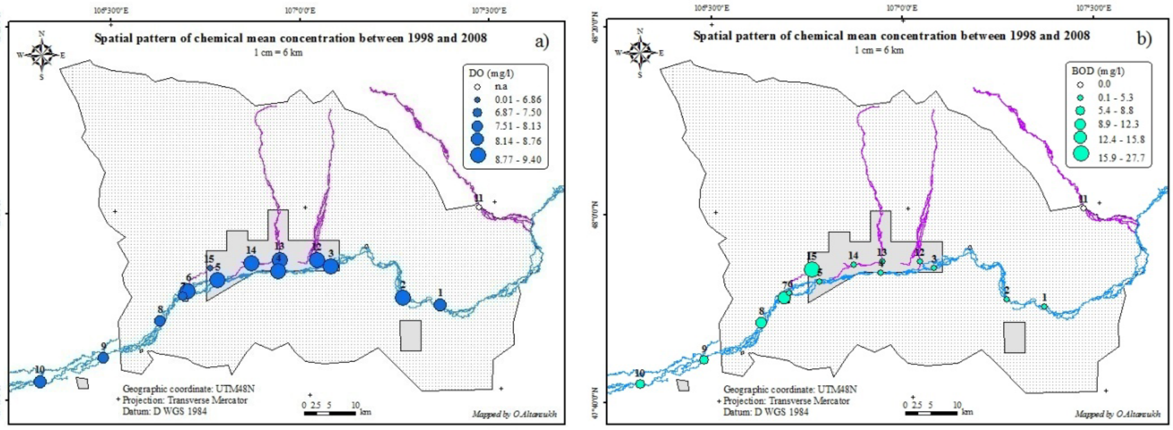

Figure 5. Spatial distribution of average concentrations of DO and BOD_5

3.2.3 Nutrients

The spatial distribution of average nutrient concentrations, NH_4^+, NO_2^-, NO_3^- and PO_4^3, are shown in Figure 6. Even though these four determinants are variable across the study area, the upper reaches of the river and tributaries have relatively low nutrient levels, which reflect the minimal impacts of human activity. The western section of the Tuul River, on the other hand, has higher concentrations of nutrients due to discharge from the treatment plant, where both nitrogen and phosphorus are higher. The lowest point of the river generally has low nutrient concentrations possibly due to the self-purification and biogeochemical processes in the river (Figure 6a-c).

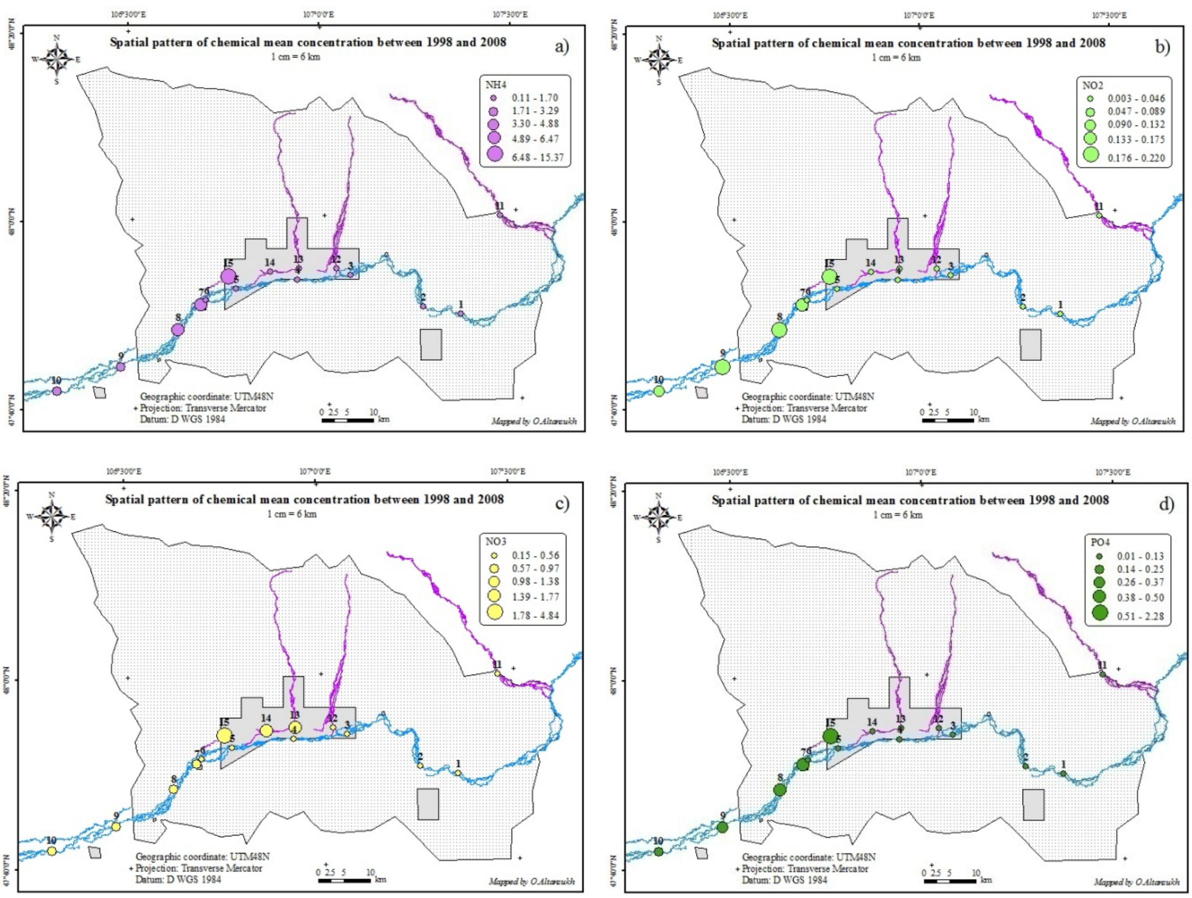

Figure 6. Spatial distributions of mean concentrations of nutrients between 1998 and 2008

Overall, NO_3^- concentrationsalong the Tuul River are low except for the inflows, where the anthropogenic activities strongly occur (Figure 6c). NO_2^- concentrations are relatively uniform up to the 7th sampling point and then decrease beyond the 7thsitereflecting the nitrification processes taking place down the river system (Figure 6b). In terms of NH_4^+ and PO_4^{3-},the same patterns canbe seen from Figure 6a, d. Those increments of nutrient concentrations at sampling point 7 are largelycontrolled by the point pollution sources.

3.3 Inter-relationship of Hydro-chemicals

To assessthe relationships among determinants, the Pearson correlation for average water hydro-chemical pairs have been calculated (Table 4). For pH, there is a statistically significant positive correlation only with calcium, magnesium, bicarbonate and nitrate.SS displays statistically significant correlations with all determinants except pH and NO_3^-. There are also significant positive correlations among major dissolved cations and anions. DO has a clear negative relationship at the 0.01 significant level. Nutrients have mostly positive correlation with other hydro-chemicals except DO. According to the Pearson's correlation, there is a perfect positive relationship of 0.99 between ammonium and biological oxygen demand, at the 99 percent level; the weakest correlation is 0.56 between ammonium and calcium at the 95 percent level. Correlations between DO and NH_4^+, PO_4^{-3} are the reverse at -0.95.

Table 4. The Pearson correlation for average bi-hydro chemicals

	pH	SS	DO	BOD_5	Ca^{+2}	Mg^{+2}	Na^++K^+	SO_4^{-2}	Cl^-	HCO_3^-	NH_4^+	NO_2^-	NO_3^-	PO_4^{-3}
pH	1.00													
SS		1.00												
DO		**-0.73	1.00											
BOD_5		**0.88	**-0.92	1.00										
Ca^{+2}	**0.77	**0.77		*0.58	1.00									
Mg^{+2}	**0.72	**0.69			**0.92	1.00								
Na^++K^+		**0.91	**-0.92	**0.96	*0.60		1.00							
SO_4^{-2}		**0.94	**-0,82	**0.87	**0.80	**0.77	**0.90	1.00						
Cl^-		**0.93	**-0.89	**0.93	**0.74	**0.70	**0.95	**0.98	1.00					
HCO_3^-	**0.82	**0.73			*0.97	**0.86		**0.73	*0.66	1.00				
NH_4^+		**0.87	**-0.95	**0.99	*0.56		**0.96	**0.89	**0.95		1.00			
NO_2^-		**0.77	**-0.85	**0.78	*0.58	**0.71	**0.82	**0.88	**0.89		**0.86	1.00		
NO_3^-	**0.89				**0.85	**0.81		*0.57		**0.92			1.00	
PO_4^{-3}		**0.88	**-0.95	**0.98	*0.60	*0.56	**0.97	**0.90	**0.96		**0.99	**0.88		1.00

Correlations are shown only when they are significant. * Correlation is significant at the 0.05 level (2 tailed)

** Correlation is significant at the 0.01 level (2 tailed)

3.4 Temporal Trends in Water Quality

Annual average values of hydro-chemicals between 1998 and 2008 have been subject to temporal trend analysis. Due to the wide range of data (NH_4^+ 0.05-12.11, BOD_5 1.28-30.07 and PO_4^{-3} 0.005-0.818)actual values have been transformed to log10 values. In case of DO, primary data has been used for the analysis. For the slope calculation of the trend, all actual datasets were used.

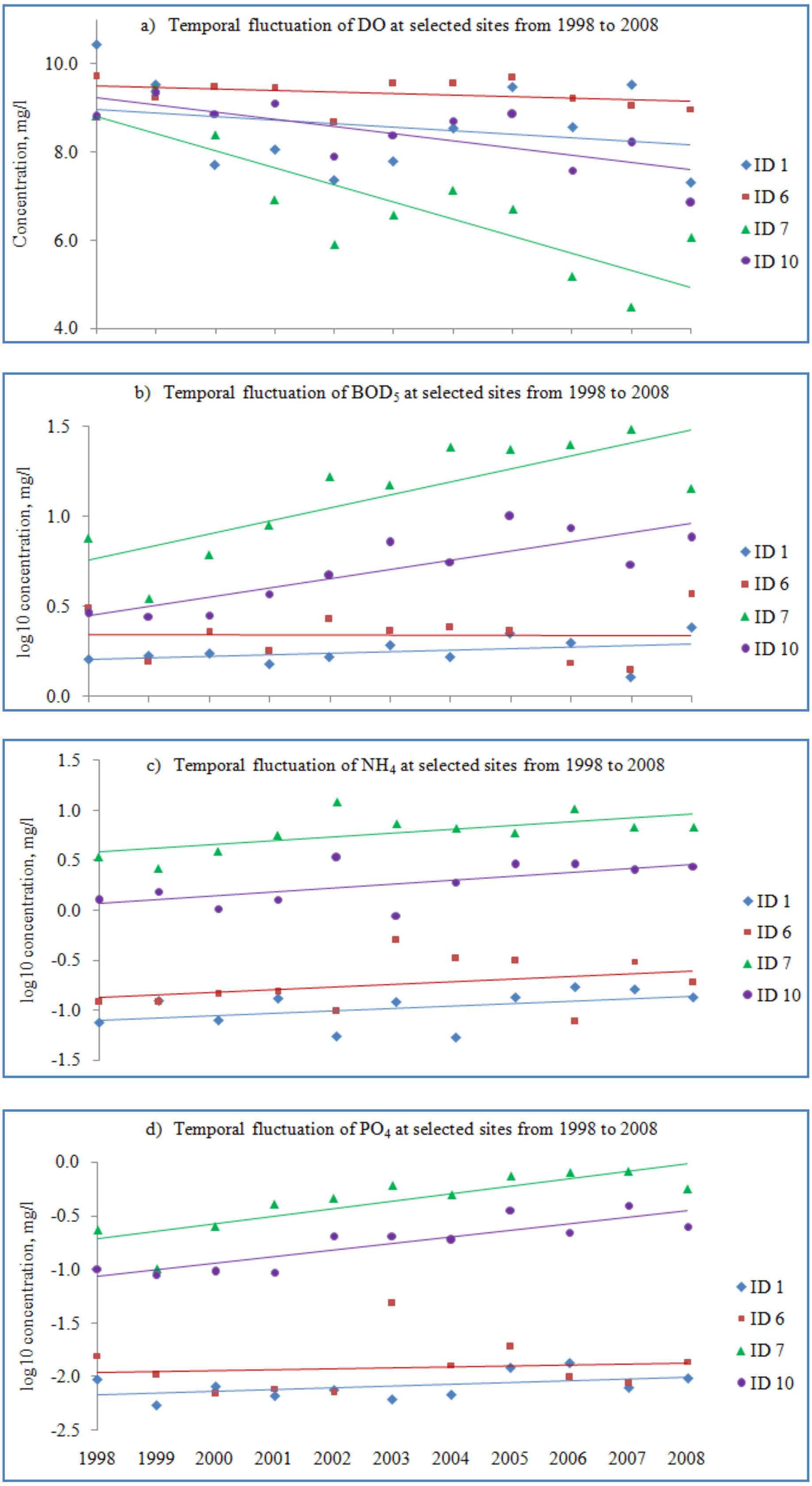

Figure 7. Temporal fluctuations of quality variables at selected sites from 1998-2008

The time-series of NH_4^+, BOD_5, PO_4^{-3} and DO at the monitoring sites 1, 6, 7, 10 are shown in Figure7. It shows trend lines at the selected sites. Calculations of the slope of all hydro-chemical variables using actual datasets and results of analysis at 14 sampling points are shown in Table 5. Positive values in the table indicate the trend is upward, negative values downward; a 0.0 value indicates there is no obvious trend.

Table 5. Trend analysis of water determinands

ID	pH	SS	DO	BOD_5	Ca^{+2}	Mg^{+2}	Na^++K^+	SO_4^{-2}	Cl^-	HCO_3^-	NH_4^+	NO_2^-	NO_3^-	PO_4^{-3}
1	-0.1	-0.3	-0.1	0.0	0.1	0.0	0.2	0.1	0.1	-0.7	0.0	0.0	0.0	0.0
2	-0.1	0.1	-0.1	0.1	-0.4	-0.2	0.0	0.3	0.4	-0.7	0.1	0.0	0.0	0.0
3	0.0	-0.7	-0.1	0.1	1.0	0.0	0.5	0.2	0.2	3.5	0.0	0.0	0.0	0.0
4	0.0	-1.1	-0.1	0.0	-0.1	0.0	-0.3	0.1	-0.1	-1.1	0.0	0.0	0.0	0.0
5	0.0	-2.0	-0.1	0.0	-0.1	-0.1	-3.2	-0.1	-0.2	-3.5	0.0	0.0	0.0	0.0
6	0.0	-0.9	0.0	0.0	-0.1	0.0	-0.3	0.1	0.0	-1.4	0.0	0.0	0.0	0.0
7	0.0	10.4	-0.4	2.1	2.0	0.3	4.3	4.1	3.5	7.1	0.4	0.0	0.0	0.1
8	-0.1	4.4	-0.2	1.3	0.9	0.1	-0.1	1.3	1.1	-0.1	0.1	0.0	0.1	0.0
9	-0.1	2.6	-0.3	0.5	0.6	0.6	0.4	1.5	0.6	-0.1	0.2	0.0	0.1	0.0
10	0.0	3.4	-0.2	0.6	0.7	0.2	0.8	1.8	1.2	0.3	0.2	0.0	0.0	0.0
11	0.0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	0.0	0.0	0.0	0.0
12	0.1	-0.5	-0.1	0.1	n.a	n.a	n.a	-0.3	n.a	-7.1	0.0	0.0	0.0	0.0
13	0.0	0.6	-0.2	0.1	2.6	-0.6	n.a	5.0	0.7	9.0	0.0	0.0	0.3	0.0
14	0.0	-0.5	-0.2	-0.1	0.9	0.2	0.0	3.3	1.5	-4.4	0.0	0.0	0.4	0.0

There is a slight downward trend in DO at sampling point 1 and an unclear trend at 6. Along the Tuul River, there is a considerable downward trend with slope -0.4 and a reflecting the impact of man's activities. BOD_5 has an upward trend that is inversely related to DO variability. In terms of ammonium concentration, there are upward trends at selected sites along the Tuul River (Figure 7c),which may reflect the population growth, industrialization and urbanization since 1990s. At most of the sites except along the lower reaches phosphorus does not display a clear trend (Table 5). Increased concentrations of most of the chemicals at site 7 could be due to improper treatment of the central plant. Certainly, there are upward trends in NO_2^- and NO_3^- related to NH_4^+ trend due to the process of nitrification, but not clearly seen from Table 5.

3.5 Seasonal Variability of Water Quality

Average values of each season were calculated and used to make assessments of seasonal variability. The summer season covers the period from June untilthe end of August, autumn from September to November, winter from December to February and spring from March until May (Figure 8). Because the data range is so wide, actual values have been transformed to log 10 values.

Figure 8 demonstrates that high concentrations of DO tend to occur in autumn and lower values likely to occur in winter. There is a steady increment in DO from winter to autumn. This is most likely due to the fact that the river freezes, preventing interaction between water and other natural components. As the temperature rises, then ice melts, flow resumes and turbulence occurs, allowing natural re-aeration to take place. Low DO and high BOD_5 concentrations occur in winter, but this relationship is reversed in the summer, when DO values are high and BOD_5 is low. This is caused by the combination of constant discharge from CWTP throughout the entire year and changeable river flow. Insufficiently cleaned waste water from the treatment plant is known to have high BOD_5, NH_4^+, NO_2^-, NO_3^- and PO_4^{-3} concentrations, which can result in major DO reduction.

Figure 8 shows that the general distribution of ammonium and phosphorus are the same as BOD_5 due to the reason referred to above. Surface runoff is another non-point source of NH_4^+ and PO_4^{-3} during times of snow melt in the spring and rainfall in autumn. High concentration of NH_4^+ and PO_4^{-3} tend to occur in winter due to a lack of river discharge.

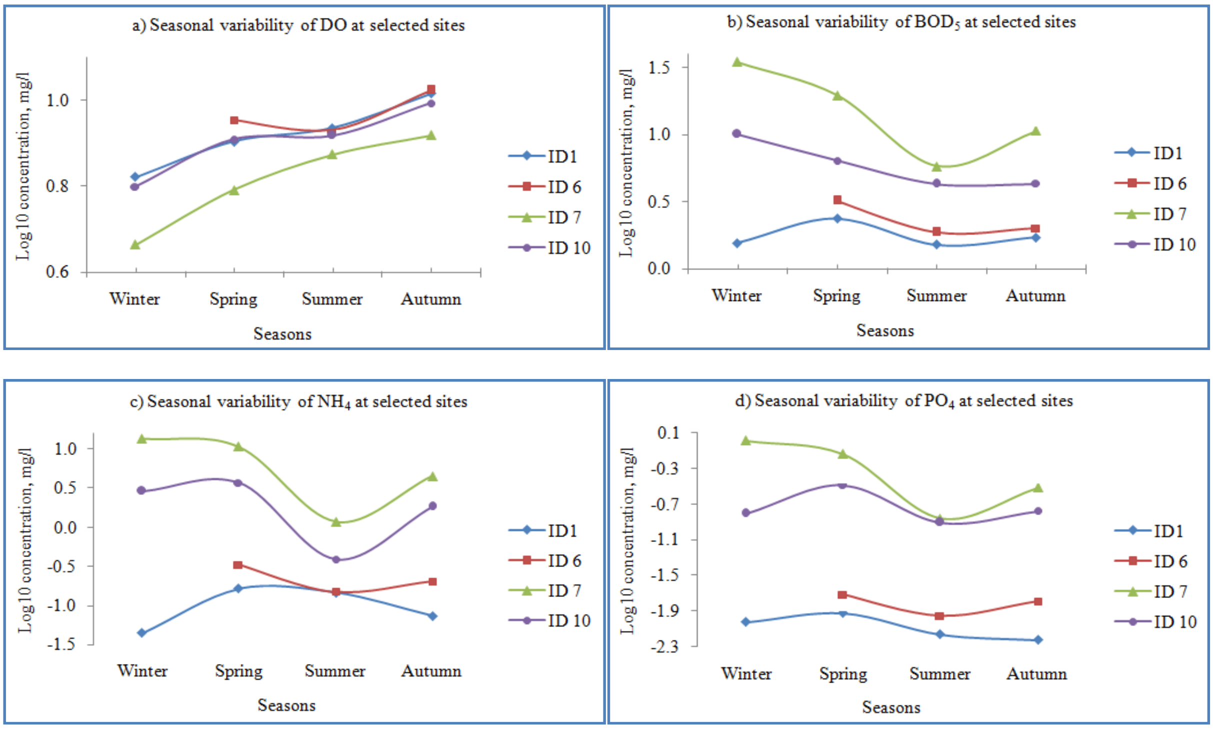

Figure 8. Seasonal changes of quality variables at selected sites from 1998-2008

The seasonal variability of ammonium concentration depends on both natural and human processes. Higher values in winter time are related to low river flows and high from the CWTP. Similar concentrations in winter and spring can be correlated to a similar match between surface runoff, and discharge from the treatment plant. Lower concentrations in summer are the result from a combination of normal river flow, dilution and re-aeration and nitrification. Higher level in the autumn are related to rainfall and runoff, which wash away nitrogen from the catchment area.

Throughout the entire year, the highest are measured at the sampling point 7, which is associated with discharge from the CWTP. This kind of general pattern can be seen in almost all rivers which run through the city and affected by WTP. Further evidence for the role of point source pollution is seen in Figures 4-6.

3.6 Water Quality Classification System

Hydro-chemical variables have been used to assess the classification of river water quality as defined by the Mongolian Water Quality Classification and the EU water standard shown in Table 6. For the most recent assessment, the average of the last five years (2004-2008) have been calculated and compared to the threshold values (Table 2). Parameters, which are not mentioned in Mongolian classification, have been excluded from the quality determination and comparison.

Figure 9a shows the river water quality classes compared to the Mongolian classification system. All sites fall into class 4 or 5; the rest of the classes are not shown onthe map due to high concentrations of NH_4^+. The values of pH and NO_3^- fall within classes 1 and 2. For SS and DO concentrations, classes 1-4 are estimated. Calcium, magnesium, sulphate and chloride concentrations belong to class 1. Depending on specific valueof the remaining variables falls into classes 1 to 5. The worst variable is ammonium, which belongs to classes 4 and 5 even in the upstream section. The reason for this might be the removal of atmospheric deposition by rainfall in the upstream section of the river since water sampling takes place in a warm period of the year. Obviously, high concentrations of ammonium are strongly related to the anthropogenic influences in the downstream sections of the river andthe city centre. This analysis confirms the poor quality of the river system in the study area.

In terms of EU standards, the Tuul River is poor quality throughout the downstream section as shown in Figure 9b. In contrast, the quality of the upstream stretch of the riverand associated tributaries fall within EU standards. However, most of the pass values were close to the threshold value.

Table 6. Mean values of hydro-chemicals from 2004-2008 for each monitoring sites

ID	pH	SS mg l^{-1}	DO mg l^{-1}	BOD_5 mg l^{-1}	Ca^{+2} mg l^{-1}	Mg^{+2} mg l^{-1}	SO_4^{-2} mg l^{-1}	Cl^- mg l^{-1}	NH_4^+ mg l^{-1}	NO_2^- mg l^{-1}	NO_3^- mg l^{-1}	PO_4^{-3} mg l^{-1}
1	7.0	5.44	8.68	1.92	13.33	1.73	6.10	3.12	0.13	0.004	0.31	0.010
2	7.2	9.20	8.72	2.34	6.90	0.98	6.14	5.33	0.52	0.014	0.42	0.032
3	7.3	9.76	9.36	2.55	19.88	3.18	5.37	2.88	0.25	0.020	0.26	0.008
4	7.7	5.38	9.30	2.03	9.20	2.01	4.39	2.14	0.14	0.011	0.20	0.014
5	7.4	13.50	9.16	1.84	10.80	1.30	5.17	2.35	0.14	0.008	0.32	0.009
6	7.3	9.80	9.29	2.27	12.57	2.11	8.88	4.33	0.24	0.014	0.43	0.013
7	7.4	70.39	5.91	23.30	32.98	5.01	50.22	39.55	7.26	0.160	0.58	0.686
8	7.5	53.83	7.05	17.00	28.21	5.66	39.17	28.05	5.72	0.226	1.10	0.571
9	7.5	34.11	6.92	8.37	32.17	11.60	38.34	25.90	3.81	0.245	1.11	0.344
10	7.6	32.81	8.04	7.41	25.53	5.19	32.48	22.54	2.56	0.183	1.10	0.280
11	7.1	n.a	n.a	n.a	n.a	n.a	n.a	n.a	0.29	0.003	0.18	0.023
12	7.8	3.56	9.02	2.38	n.a	n.a	2.22	n.a	0.37	0.003	0.17	0.018
13	8.1	34.03	9.22	3.45	n.a	1.50	38.02	14.60	0.34	0.033	2.90	0.030
14	8.1	7.58	7.91	3.27	27.26	6.28	13.98	10.62	0.47	0.036	2.31	0.134

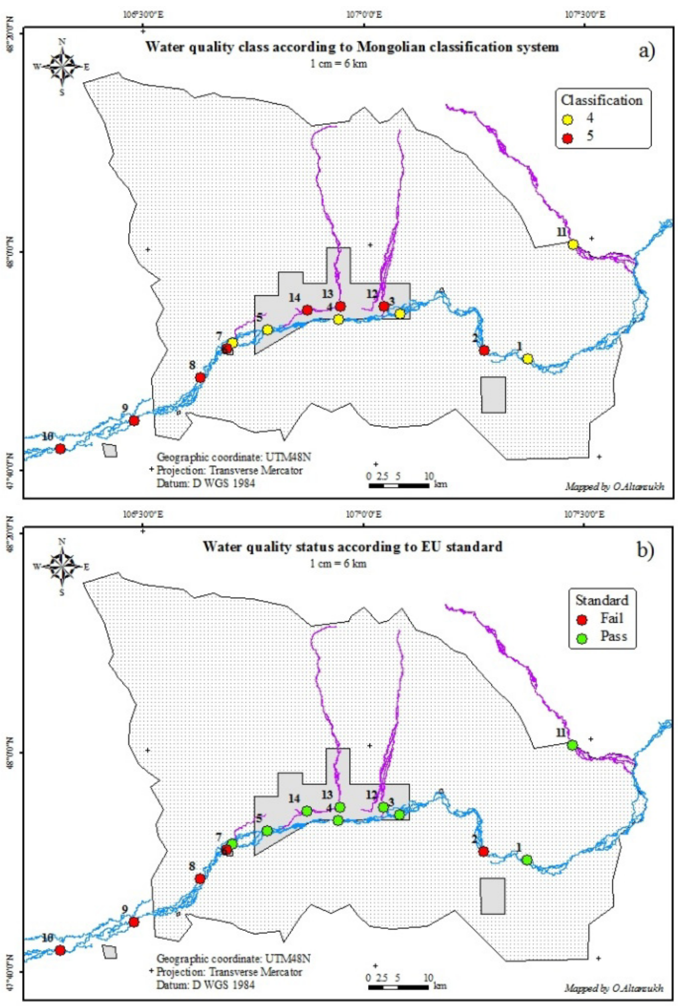

Figure 9. The water quality status according to a) Mongolian classification and b) EU standard

3.7 Implications of Study

Evidently, there is a need to improve the water quality in the Tuul River system in the area surrounding Ulaanbaatar city in order to bring it up to the standards required to meet class, I or II of Mongolian Water Quality Classification. The water quality and classification analysis have shown the river system is failing Mongolian standards, with 6 hydro-chemicals out of 12 falling into the lowest classes 4 and 5. Spatially, water quality decreases downstream along the river. Several point and non-point pollution sources exist in the study area. Water quality improvement of the river system is thus of vital importance. A water quality modelling study is followed to assess the effectiveness of different scenarios, which could be used to improve water quality in the future.

In many countries, pollution results from both point sources such as industrial wastewater treatment works and non-point sources such as agricultural runoff when excessive quantities of fertilizers are applied to crops. Impacts from urban and rural point sources remain a serious problem with regard to surface water nutrient concentrations (Jin, Whitehead, & Hadjikakou, 2010). Naturally, the upstream parts of the river have more ability to self-purify through processes of re-aeration and turbulence as a result of flow through mountainous areas than the more sluggish downstream sections (Altansukh, 2000).

At the moment, the agricultural runoff has not yet caused serious pollution of the river system in the study area. Pollution is more associated with urbanization, industrialization and population growth in settlement areas, and more related to densely concentrations of tourist camps in the upstream section of the Tuul River.

4. Conclusions and Discussion

This study has provided a comprehensive water chemistry assessment of the Tuul River system in the area surrounding Ulaanbaatar city, Mongolia, using an extensive dataset collected between 1998 and 2008, by CLEM. It presents the spatio-temporal assessment and seasonal pattern of 14 hydro-chemical determinants at 15 monitoring sites in the study area. The results suggest that the major dissolved chemicals such as Ca^{+2} and HCO_3^- are controlled by mineral dissolution. Atmospheric deposition also has an important influence on the concentration of HCO_3^- due to excessload of CO_2 from different anthropogenic sources. Human activity in the region has a significant impact on BOD_5, DO and nutrient concentrations. Increments of hydro-chemicals are strongly associated with CWTP operation. The concentration of general anions, cations and pH values fall within the normal range over the entire study area. Generally, nitrate concentrations are low and nitrite concentrates are high along the rivers, which mean that pollution is newly generated, and the source islocated close to that point. Phosphate concentrations are mainly linked topoint sources. Estimated values of ammonium are very high in all monitoring sites which may be associated with atmospheric deposition and surface runoff in the catchment area. It also has a strong impact on water quality classification. The level of pollution in the downstream section (sites 7-10) of the Tuul River strongly depends on how well water has been treated when discharged from the CWTP, which is the most important point pollution source in the downstream section of the Tuul River in the study area. There is a process of natural purification within the river, buteven 50 kms downstream of the city pollution can still be detected.

According to the Mongolian WQCS, all sections of the Tuul River and its tributaries in the surrounding area of Ulaanbaatar city belong to moderately and heavily polluted waters due to high concentration of ammonium. However, based on EU water quality standards the quality of water in the downstream section of the Tuul River fails. In order to change this situation, improvement of the operation efficiency of CWTP becomes crucial to improve the water quality significantly. Accordingly, a modelling of water quality with different scenarios such as certain limits on chemical concentrations of discharge from the CWTP and artificial increment of DO concentrations have important roles in the decision making system. DO concentrations can be artificially increased using bull stone wall (not weir) which has big enough holes that fish and sediment can easily pass through. The penetration theory by Higbie, 1935 and a surface renewal model that formalized Danckwerts in 1951 are theoretical part of the DO artificial increment method. This method is more eco-friendly (economically and ecologically) and works more effectively over the long period. Also, there are several advantages of this method, which include i) materials that can use to build the wall are natural, ii) there is no extra operation cost after the wall built, iii) no negative impact on the river system, and aquatic fauna and sediment can easily pass through by holes between bull stones, iv) works efficiently for a long period, v) easy to stop the operation (just take out stones), and vi) an artificial pond will not be created in upstream. However, there are also some disadvantages such as i) not applicable to large rivers, ii) the wall may collapse in the fact of strong flows, and iii) heavy machinery such as crane is required.

The river system remains highly vulnerable to pollution. With increasing population and industrialization in the future, it is recommended that the Water Authority of Mongolia should define vulnerable zones and protection distances from both river banks and to restrict future developments in these areas which may have a negative impact on river ecological system. Furthermore, the Mongolian Government should improve the operational efficiency of the CWTP in order to reduce the negative impact on surface water pollution. Perhaps a new wastewater treatment plant is needed for Ulaanbaatar city.

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