ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

A Study of Spatial Distribution of Water Pollutants and Water Quality in Puget Sound Basin, Washington State, U.S. Based on GIS

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Abstract: *The water pollution has gradually become the most important issue around all of the world and the water quality problem has been concerned by many countries. In this study, GIS technology is applied to monitor data and WQI is used to analyze and predict the distribution of the water quality in the Puget Sound basin, U.S., which can provide a intuitive visual suggestions as well as offer improvement strategies for water pollution control.*

Keywords: *Water Pollutant, Water Quality, Spatial Distribution, WQI, Kriging, GIS Technology*

1. Introduction

Since the 1980s, water quality and water environment deterioration trend had been a threat to human's health, and water environmental problems have become the research hot spot in the global world.

Puget Sound area, as the most contaminated estuary in US, it is of paramount importance that finds the spatial distribution of relevant pollutants and water quality so as to control water pollution and implement strategies. According to department of Ecology, Washington State, U.S., preliminary water data are recorded and then converted to Water Quality Index through complex calculations. Then with the datasets, thematic interpolation maps of 8 water quality constituents respectively and overall water quality are created using the GIS technology, which can analyses the current water pollution and provide intuitive visual suggestions.

1.1 Basic Information about Puget Sound Basin, Washington State, U.S.

Figure 1: Map of Puget Sound basin

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

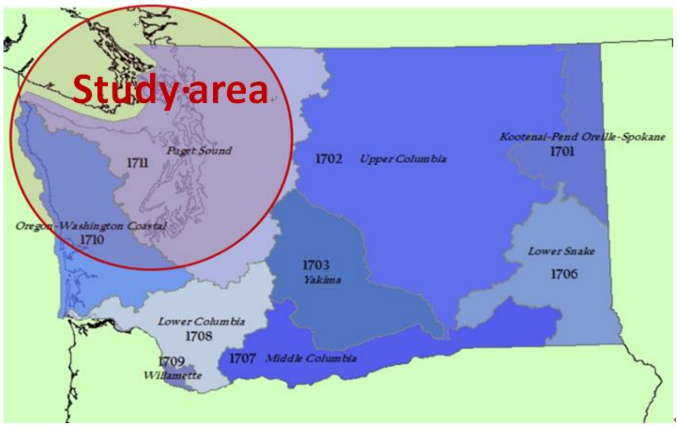

Figure2: Puget Sound basin in the Washington State of U.S.

Puget Sound, the second largest estuary in the United States, is an arm of the Pacific Ocean in western Washington, extending south from the Strait of Juan de Fuca through Admiralty Inlet, where it meets 19 different river basins.

1.2 Water Pollution Issues in Puget Sound basin

Puget Sound region today is very different from the Puget Sound of the past. There is no doubt that Puget Sound is in trouble, but one of the major issues in Puget Sound is water pollution. Every time it rains in the basin, thousands of pounds of toxic pollutants flow overland, eventually winding up in the Sound. Critical habitat has been lost to development.

As well as the highly urbanized area, there are many types of water pollutants threatening Puget's aquatic environment. Pesticides, oil, industrial effluent, nuclear waste and metals can be toxic to aquatic organisms. Other materials such as sewage, animal waste and sawmill waste may not be directly toxic, but could overload the capacity of the receiving water to assimilate them; Consequently, giving rise to poisonous conditions. In addition, sewage and animal waste present in amount that impact intangibly on estuarine ecosystem may render marine shellfish unsafe as food and lead to closure of commercial shellfish beds. Furthermore, nutrients in detergents and fertilizers often stimulate plants growing in large number and scale, which may result in reduction of DO. Finally, certain pollutants like heavy metal can bio- concentrate or bio-accumulate via food chain. In a conclusion, the water pollution eventually jeopardizes humans potentially.

1.3 River and Stream Water Quality Monitoring Programme

The Washington State Department of Ecology has built the statewide water quality monitoring network, from 207stations including 72 long-term stations and 135 basin stations. River and Stream Water Quality Monitoring Programme was launched by the department monitoring by water year from the different types of stations to collect stream and air temperature data at 30-minute intervals, recording instruments at 30 to 50 stations, generally from June through September.

All in all, the programme is to provide timely and accurate water quality data and data summaries for Department of Ecology and other researcher to make further exploration. Routine monitoring data are then summarized by a technique called the "Water Quality Index" (WQI). These data are used for a variety of purposes such as determination of status and trends in stream water quality statewide.

2. Methodology

2.1 Literature Review

The importance of the water pollution and water quality assessment by using GIS has been studied by researchers over years. A.P. Marchant et al.[1] improved IST , a custom built GIS application, to assess the potential for water resource contamination due to new development in London, UK. Besides, using GIS techniques are further utilized in the formulation of a raw water monitoring programme to evaluate pollution risks to water supply intakes by J.A. Foster [2]. A. Calera Belmonte [3] and his team

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

from Spain developed a specific GIS in order to better manage the aquifer system as well as expedite the control and monitoring, in real time, of the exploitation plans.

As for water quality assessment, there is no single measure that can describe overall water quality for all types of water, consequently a composite index including many indicators is developed. However, varied indicators are chosen according to specific study areas and water quality. Then these parameters are aggregated into water quality data to illustrate the water quality. According to global drinking water quality index development and sensitivity analysis report, the most common methodology is that selected indicators are weighted according to their perceived importance to overall water quality and the overall index is calculated as the weighted average of all observations of interest.

An index of river water quality in Taiwan was developed by Liou et al.[4] that is a multiplicative aggregate function of standardized scores for temperature, pH, toxic substances, organics (dissolved oxygen, BOD, ammonia), particulate (suspended solids, turbidity), and microorganisms (fecal coliforms).In 2006, ZHU **s**uggested a qualitative biotic stream condition evaluation ,meanwhile, besides the biological method, a chemical water quality index based on data from 18 streams in one lake basin in northern Alabama that represent the concentration of seven water quality parameters (total nitrogen, dissolved phosphorus dissolved lead, dissolved oxygen, total, particulate and pH) was recommended according to Tsegaye et al. [5] .In terms of overall water quality index**,** Sargaonkar and Deshpande [6] conducted research on Indian rivers and established overall index of pollution (OIP) containing measurements and subsequent classification of pH, turbidity, dissolved oxygen, BOD, hardness, total dissolved solids and the like.

2.2 Data Preparation

From the statewide water quality monitoring network established by The Washington State Department of Ecology, the river and stream water quality monitoring involves routinely several indicators of water quality collecting data from the specific stations and different methods from June through September every year.

(1) Water Quality Index (WQI)

Ecology's stream monitoring Water Quality Index (WQI) was developed to address non-technical questions about general water quality. It is designed to rate general water quality based on station monitoring results from monthly grab samples (preliminary data) which have been converted to scores following a fairly complex methodology which will be discussed later.

8 water quality constituents of stations chosen from 17 water quality indicators are combined except non-standard elements like metals and results aggregated over time to produce a single score for each station and each year.8 water quality constituents include FC(Fecal Coliform Bacteria),OXYGEN,PH,SUSSOL(Total Suspended Solid),TEMP(Temperature),TPN(Total Persulf Nitrogen),TP-P(Total Phosphorous),TURB(Turbidity).

Two types of evaluations: score by constituent and score by month

In general, there are three different classifications of water quality.

Table 1: Criteria of water quality classifications

WQI score(1-100)	Classifications
81-100	Lowest concern
41-80	Marginal/Moderate concern
1-40	Highest concern

(2)Selection of sampling data and Data input

50 monitoring station around the Puget station is selected and exported data **called “50 sites”.** A year of preliminary water quality data recorded by each station is input into excel.

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

Table 2: A excel of preliminary data of 8 water quality constituents from station 10A70

Date	Time	FC		OXYGEN	PH	PRESS	SUSSOL		TEMP	TP_P	TPN	TURB
		(#/100ml)		(mg/L)	(pH)	(mm/Hg)	(mg/L)		(deg C)	(mg/L)	(mg/L)	(NTU)
10/19/2011	12:50	17		11.3	7.68	762	8		9.6	0.0463	0.375	4.6
11/16/2011	13:00	10		12.7	7.67	757.936	8		4.5	0.0347	0.304	3.6
12/21/2011	14:15	12		13.4	7.53	770.89	12	J	4	0.0383	0.404	2.5
1/25/2012	12:30	22	J	12.7	7.61	768.858	109	J	5.1		0.45	21
2/29/2012	10:05	12	J	12.86	7.38	748.03	147	J	3.7	0.128	0.306	20
3/28/2012	13:10	20		11.9	7.68	755.65	13		7.2	0.0259	0.336	2.5
4/25/2012	12:20	15		12	7.45	754.888	146	J	7.7	0.0965	0.137	35
5/23/2012	12:35	52	J	11.8	7.63	763.27	68		8.3	0.0499	0.13	18
6/27/2012	14:00	9		11.7	7.58	764.286	14		11.3	0.0217	0.13	5.8
7/25/2012	12:00	46		10.8	7.36	764.032	55		13.6	0.0709	0.092	35
8/29/2012	12:45	40		10.6	7.47	766.572	33		13.88	0.0721	0.168	36
9/26/2012	12:15	41		11	7.71	766.064	36		11.27	0.0839	0.224	45

(Common data qualifiers: U - not detected at the reported level, J - estimated value)

Times are local (Pacific Standard or Pacific Daylight Savings).

Colored background: indicates that result exceeded water quality standards -OR- contrasted strongly with historical results.

2.3 Data disposing

2.3.1 Procedure and Methods

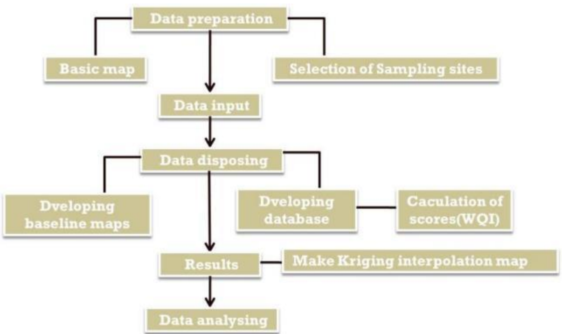

Figure 3: Technical road map

2.3.2 Developing baseline maps

As mentioned before, shape files of Washington State, county, water bodies, coastline area are added and display titled 'county map'.

As for polluted areas, shellfish bio-toxin closure zone, shellfish harvesting forbidden areas, Areas of extreme concerns are combined and created new layer called 'pollution areas'.

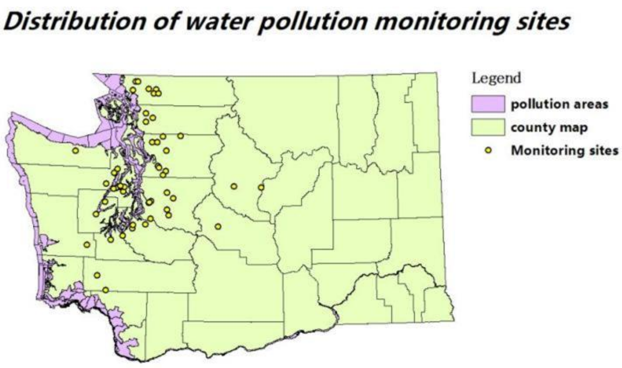

Figure 4: Baseline map

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

2.3.3 Data statistics --Calculation of Water Quality Index (WQI) of Each Constituent

(1) Convert preliminary results to an index score ranging from 1 to 100

Every original result in the selected date range is converted to an index score by a quadratic equation according to different types of water quality constituent.

In other words, the particular formulas used for a particular station depended on the stream class or ecoregion for that station.

(2) Aggregate index scores.

After calculation of WQI by constituent, table including WQI scores of 8 water quality constituents from 50 stations.

Table 3: WQI by constituent

FID	Station	1FC	2OXYGEN	3PH	4SUSSOL	5TEMP	6TP_P	7TPN	8TURB
0	01A050	80	80	97	38	85	69	42	48
1	01A120	98	87	86	47	80	95	51	53
2	01A140	99	91	80	1	79	36	27	4
3	01F070	96	80	98	27	66	21	54	32
4	01G070	97	95	96	9	87	72	46	11
5	01N060	53	67	92	89	79	1	52	83
6	01U070	55	74	94	85	79	1	65	77
7	03A060	99	80	67	51	85	99	84	76
8	03A080	95	87	94	60	80	97	65	66
9	03B050	78	82	83	77	81	34	76	81
10	05A070	91	91	94	60	80	91	79	63
11	05A090	89	76	95	70	73	90	78	73
12	05A110	93	79	96	70	74	98	79	73
13	05B070	94	80	93	37	77	36	55	42
14	05B110	97	89	95	68	74	52	85	65
15	07A090	93	92	93	76	78	87	89	85
16	07D050	83	88	92	68	70	85	83	77
17	07C070	90	92	93	80	74	95	94	84
18	07D050	83	88	92	68	70	85	83	77
19	07D130	85	80	90	71	83	93	88	82
20	07P070	59	68	91	82	84	31	62	86
21	07R050	78	7	83	81	77	1	47	69
22	08C070	85	93	84	86	75	91	97	99
23	08C110	90	85	97	98	91	95	100	100
24	09A080	75	91	94	82	76	64	65	86
25	09A190	92	83	94	76	74	57	84	71
26	10A070	63	17	92	85	75	33	21	70
27	10C095	88	90	98	54	87	87	50	51
28	11A070	88	89	96	19	87	84	16	35
29	12A110	97	89	97	80	73	91	79	77
30	12B070	59	93	96	85	79	1	80	89
31	13A060	9	77	96	60	80	1	41	71
32	15A070	87	95	96	84	85	27	76	86
33	15B050	77	77	88	86	74	96	81	91
34	15C070	83	91	78	86	86	18	67	87
35	15F050	59	86	84	96	88	39	64	91
36	15L050	88	87	92	79	82	89	83	79
37	15M070	77	86	89	87	91	55	87	96
38	15N070	90	91	95	80	92	44	72	91
39	16A070	85	88	88	71	89	96	67	87
40	16C090	80	92	96	94	88	100	97	91
41	17A060	99	97	87	86	94	98	100	88
42	17G060	92	88	97	80	90	100	81	76
43	18B070	42	64	83	94	82	55	60	87
44	23A070	97	93	89	21	94	95	15	14
45	23G070	81	92	95	66	59	58	61	72
46	26F050	85	78	92	61	49	74	59	65
47	39B090	63	75	83	94	66	48	46	89
48	45A110	99	81	93	81	77	96	100	93
49	46A070	97	76	92	49	73	91	93	70

Score by month

WQI analyses including many years can be aggregated into a single score. A score for each measured water quality constituent for each month is determined as the mean of all scores for that constituent and that month. The WQIs for the different constituents are then aggregated for each month by calculating a simple average and subtracting a penalty factor for monthly scores smaller than 80. The penalty factor is (85-WQI Score)/2.The overall WQI for a station is the average of the three lowest-scoring months based on the above statistics, the WQI by month is calculated as well as the overall WQI of each station.

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

Table 4: WQI by month and overall WQI scores

FID	Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	overall WQI
0	01A050	90	81	97	60	97	79	69	75	64	63	82	87	62
1	01A120	96	85	100	96	99	90	97	83	68	68	81	93	72
2	01A140	79	31	73	46	92	48	91	81	59	58	52	62	42
3	01F070	95	38	98	41	60	38	62	66	53	78	81	73	39
4	01G070	80	45	83	72	91	83	97	92	75	58	58	66	54
5	01N060	61	67	84	64	87	62	54	64	74	47	70	80	54
6	01U070	82	57	92	46	92	81	89	81	80	63	64	81	55
7	03A060	96	79	98	97	99	98	99	89	74	81	78	94	77
8	03A080	68	76	97	99	99	99	97	95	95	94	93	84	76
9	03B050	95	94	98	86	95	94	77	93	71	88	91	92	78
10	05A070	93	89	98	68	95	95	86	96	89	95	90	93	81
11	05A090	96	91	97	94	98	92	98	87	79	93	79	87	82
12	05A110	97	89	98	97	96	96	99	93	81	93	83	93	84
13	05B070	52	40	95	45	67	50	75	67	56	86	78	68	45
14	05B110	75	56	100	78	97	97	94	81	84	92	84	85	70
15	07A090	95	97	99	94	99	97	96	96	87	94	89	94	90
16	07D050	89	83	99	91	97	96	97	97	78	93	83	93	3
17	07C070	94	97	99	98	99	99	99	97	83	95	87	88	86
18	07D050	89	83	99	91	97	96	97	97	78	93	83	93	81
19	07D130	94	95	99	98	99	98	99	96	69	94	91	91	83
20	07P070	47	n/a	54	95	95	92	33	69	60	60	63	60	45
21	07R050	15	71	64	56	67	83	56	4	15	1	7	61	4
22	08C070	93	100	99	98	100	99	98	95	93	88	82	86	85
23	08C110	98	100	100	n/a	100	100	100	98	94	96	95	96	95
24	09A080	82	85	96	69	95	95	96	85	92	89	76	80	75
25	09A190	75	59	83	99	89	93	97	93	92	94	89	73	69
26	10A070	92	98	96	83	82	96	80	87	91	70	72	71	3
27	10C095	86	96	93	90	97	96	98	65	64	66	60	77	71
28	11A070	86	94	96	95	96	96	97	96	95	93	93	79	63
29	12A110	90	90	97	60	96	97	86	89	93	87	56	60	86
30	12B070	78	65	20	51	53	64	75	62	72	64	1	57	59
31	13A060	94	96	96	76	90	96	94	94	92	87	94	93	24
32	15A070	96	100	79	99	99	99	97	87	93	94	72	94	84
33	15B050	80	57	91	99	97	86	95	94	96	87	93	88	79
34	15C070	69	83	95	94	96	95	96	77	59	66	36	65	75
35	15F050	98	96	88	97	94	88	98	96	95	89	92	92	53
36	15L050	97	96	97	99	98	94	99	98	82	93	93	72	88
37	15M070	84	96	94	94	97	94	98	96	81	82	85	86	83
38	15N070	97	95	89	95	93	86	99	96	95	93	93	97	82
39	16A070	97	n/a	98	98	100	99	97	72	96	98	97	97	89
40	16C090	99	99	99	99	99	99	98	98	96	97	97	98	88
41	17A060	99	98	100	70	100	100	100	99	97	98	96	97	97
42	17G060	75	61	94	94	78	92	91	64	78	26	73	75	88
43	18B070	80	97	97	75	76	75	66	68	65	61	70	66	50
44	23A070	34	87	80	82	87	73	73	84	72	65	62	81	64
45	23G070	92	76	81	83	78	60	76	82	72	67	64	77	54
46	26F050	62	84	95	96	91	92	95	78	74	60	71	82	64
47	39B090	96	99	99	100	99	99	96	99	97	94	93	89	64
48	45A110	96	99	100	99	99	98	97	96	74	63	73	95	92
49	46A070	96	98	100	99	93	78	91	82	97	95	87	88	70

2.3.4 Developing database

Data base incorporates basic map, map of polluted areas covers and tables of Water quality indicators.

2.3.5 Developing Attribute Table (Geo Statistics Analysis)-Make Kriging Interpolation of Water Quality Data (Point Data)

Based on literature review on water quality studies, Kriging is the most common and accurate tool for water quality assessment in spatial analysis.

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

It is assumed that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation of each water quality constituent in Puget Sound basin.

Firstly, the study is to find the spatial distribution of water quality indicated by WQI of each water quality constituents.

Second, from the holistic view, the study aims to find the spatial distribution of water quality indicated by overall WQI (score) of each station.

3. Analyzing spatial data

3.1 Spatial distribution of water pollutant

Though Kriging interpolation tool, we get the following maps of 8 single indicators. From these maps, we can easily know the scores of each indicator and the situation of the main four cities near the basin.

Figure 5: Spatial distribution of WQI of Fecal coliform bacteria

Figure 6: Spatial distribution of WQI of Oxygen

Figure 7: Spatial distribution of WQI of PH

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

Figure 8: Spatial distribution of WQI of Suspended solids

Figure 9: Spatial distribution of WQI of Temperature

Figure 10: Spatial distribution of WQI of Total persulf nitrogen

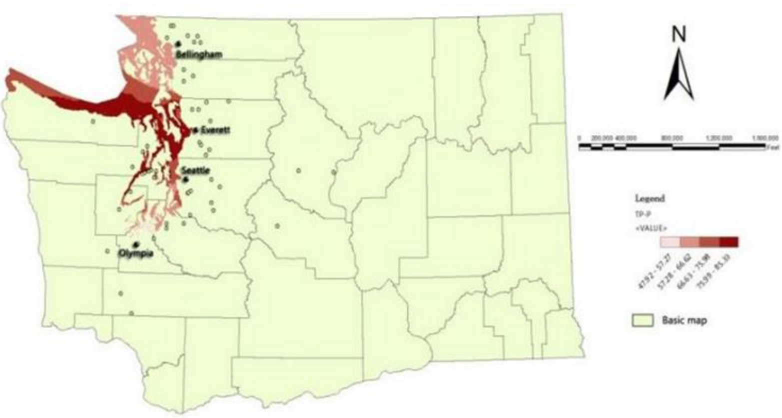

Figure 11: Spatial distribution of WQI of Total phosphorus

Figure 12: Spatial distribution of WQI of Turbidity

3.2 Spatial distribution of overall water quality

With the overall score from the calculation of WQI, we use the Kriging tool as well to make the overall score map, from this map we can easily know the whole situation of the basin and the water quality of cities near it.

Figure 13: Spatial distribution of overall scores with whole indicators

4. Results and conclusions

From the spatial distribution map, we find the overall water quality is not bad. Though the efforts of the Washington Department of Ecology, now the water quality has gradually been better than the past.

But the warning is that the water quality in the main four cities near the basin is not as good as expected. For the overall score spatial distribution, Bellingham should be concerned most. Of course, the other two cities, Olympia and Seattle also should take measures to improve their water quality.

In addition, we have some suggestions from the single indicator distribution map. With all 8 indicators, total persulf nitrogen and total phosphorus are the worst two, Olympia is suffered most, we recommend the government pay more attention to the chemical pollution sources and strictly control the discharge of industrial wastewater such as which come from the pharmaceutical factory. Meanwhile, the fecal coliform bacteria indicator in Olympia and Seattle is low, concerning about livestock farms may a good proposal for these two cities.

The most prominent feature in the spatial distribution we can see is that more people more worse. So the activities of human beings influence the water quality most. The behaviors of every citizen has affected the results.

Overall, the GIS distribution map shows us a visual situation of water quality and as well offers efficiency and accuracy data for us to study more.

ISSN 2706-655X Vol.4, Issue 4: 73-82, DOI: 10.25236/IJFET.2022.040410

5. Limitations

5.1 Deficiency in Database

5.1.1 Incomplete Polluted Areas

The polluted area used in the study only takes district relevant to shellfish into consideration. In consequence, the contaminated area displaying on the map is part of the total polluted water bodies.

5.1.2 Inaccuracy in selecting the monitoring station

The principles of selecting the stations is (1) close to the Puget Sound basin (2) record the necessary water data.While choosing the stations, some station with desirable proximity is without sufficient water information. As a result, a few stations far from stations are selected however at the sacrifice of distance. Constricted to these principles, only 50 monitoring stations are qualified. So considering the quality and quantity of chosen stations, it may adversely influence the accuracy of the final results.

5.2 Deficiency in Water Quality Index Model

- Water quality indexes are based on a pre-identified set of water quality constituents, and many other parameters such as BOD, COD are excluded.
- After calculations and summarized, these indexes contain less information than the raw data. Actually, indexes only provide a general understanding of water quality conditions but fail to give the whole picture. Site-specific decisions should be based on an analysis of the original water quality data. An index is not "a complex predictive model for technical and scientific application" (McClelland, 1974).
- Aggregation of short-term water quality data may mask real problems.   In the study, water quality index of 2012 is processed however the water quality evolves over years dynamically.
- WQI values can only give general idea of water quality and relative value compared to the satisfactory water quality.it is not explicitly stated in the situation between different functional areas as well as express the water quality in a certain water quality standard

Acknowledgment

We would like to show my deepest gratitude to Pro. ZHANG Yuanzhi as well as extend thanks to Miss. LI Xiang for all her kindness and help.

Lastly, we would also like to thank officer Scott Kellogg from government of Olympia, WA offering the GIS data.

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