



# Using principal component analysis to monitor spatial and temporal changes in water quality

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## Abstract

Chemical, biological and physical data monitored at 12 locations along the Passaic River, New Jersey, during the year 1998 are analyzed. Principal component analysis (PCA) was used: (i) to extract the factors associated with the hydrochemistry variability; (ii) to obtain the spatial and temporal changes in the water quality. Solute content, temperature, nutrients and organics were the main patterns extracted. The spatial analysis isolated two stations showing a possible point or non-point source of pollution. This study shows the importance of environmental monitoring associated with simple but powerful statistics to better understand a complex water system. © 2003 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Generally, it is admitted that under natural conditions, the climate and the topography are among the factors influencing the hydrochemistry of natural waters [1]. Specifically, the chemical composition of water is due to an interaction between several factors. Dillon and Kirchner [2] mention weathering of rocks in the drainage basin; intensity and composition of the rain waters and soil; chemical reactions between water and soil or sediment; and point or non-point source of pollution. In New Jersey, anthropogenic inputs are of main concern, especially in the northern area, which is densely populated and heavily industrialized. Therefore, its water resources are constantly being strained by the competing

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Table 1  
Recent studies conducted on Passaic watershed

Study	Location	Reference
Impact of combined sewer overflows on sediments		
Urban runoff	Newark basin	[3]
Polychlorinated dioxins (PCDD, TCDD)	Lower Passaic River	[11]
	Lower Passaic River	[12]
	Newark Bay	[13]
	Lower Passaic River	[14]
	Lower Passaic River	[15]
Lower Passaic River	[25]	
Industrial runoff in sediments		
PCBs	Newark Bay	[16]
	Lower Passaic River	[17]
Heavy metals	Newark Bay	[18]
Petroleum hydrocarbon	Newark Bay	[19]
Geochronology/sedimentology	Lower Passaic River	[20]
Impact of flood control	Newark Basin	[21]
Water quality modeling	Passaic River	[22]
	Passaic River	[23]

needs of the growing population, industrial, agricultural, commercial and recreational activities.

The National Urban Runoff Program includes lower Passaic and Newark Bay, the most recent studies of which are summarized in Table 1. Based on results of the urban and industrial runoff monitoring, the geochronology analysis of the sediment, and the water quality of Newark Bay, Walker et al. [3] suggested that the suspended sediment entering the Bay might carry significant background chemicals with it from watershed locations upstream, more precisely from Hackensack and Passaic Rivers. This is indeed a possibility that depends on a number of natural or anthropogenic factors. The weather and the drainage area geology are among the natural factors, while the urban and agricultural runoff and the industrial discharge are the main anthropogenic factors.

Upstream Newark Bay, the Passaic Valley Water Commission (PVWC) (Little Falls, NJ) maintains a long-term monitoring program aiming to produce large set of data, which might help explain and understand the evolution of the water quality impacted by natural and anthropogenic factors. There is a certain difficulty to use and interpret large sets of data resulting from long-term monitoring programs, especially if the number of variables is important. Multivariate analysis techniques, such as principal component analysis (PCA), aid in reducing the complexity of large-scale data sets and are currently widely used in environmental impact studies [4–6].

The aim of this paper is to investigate the main physical and chemical characteristic changes of the Passaic River in 1998, year in which a complete dataset of 20 parameters was available. Ideally, a statistical analysis of the data would help isolate areas of the watershed that present different characteristics due to a natural or an anthropogenic influences of point or non-point sources of pollution.

## 2. Materials and methods

### 2.1. Area of study

Passaic aquifer is located in the northern part of the State of New Jersey. It is one of the non-Coastal Plain aquifers, which include the Glacial Valley-fill aquifers, the Newark Group aquifers, the Valley and Ridge, and the Highlands aquifer system. Generally, they are not more than 9–12 m thick and consist of glacial valley-fill deposits, crystalline rocks, conglomerate, sandstones, limestone, and fractured shales. In some areas, they can be 92 m thick but also narrow and small [7]. Between 1990 and 1996, an average of 954,155 billion of gallons (bg) and 143,817 bg of surface and groundwater sources were withdrawn from Passaic watershed [8].

New Jersey Department of Environmental Protection (NJDEP) divided Passaic watershed in three Water Management areas:

- (a) Upper Passaic, Whippany, Rockaway Management Area. This watershed management area represents the area drained by waters from the upper reaches of the Passaic basin including the Passaic source down to just before the confluence point with Pompton River. Rockaway River has a drainage area of 342.18 km<sup>2</sup> and flows east to a confluence with the Whippany River a Pine Brook. Whippany River has a drainage area of 164.40 km<sup>2</sup> and is serving a population centered in, Hanover Township, East Hanover Township, Morristown, and Parsippany–Troy Hills.
- (b) Lower Passaic Saddle Management Area. It represents a 52.93 km long portion of the river in a very densely populated area, which include Newark, Paterson, Clinton, and East Orange.
- (c) Pompton, Pequannock, Wanaque, Ramapo Management Area. This is an area that drains the highlands portion of New Jersey. Pequannock River is 48 km long. The Ramapo River has drainage of about 411.52 km<sup>2</sup>, 283 of which are in New York State.

The 12 sites sampled all year long during 1998 are presented in Fig. 1. Chemical measurements were made in the field within 1 h of collection. The on-site measurements were pH and temperature. For the laboratory analysis, the samples were taken in 5 l wide-mouthed polyethylene jars and kept cool in dark. All analyses were made in the 14 days after sampling.

### 2.2. Origin of data

The data used in this study are part of a database maintained by PVWC. The 19 measured parameters, their units and abbreviation, as well as the methods used for their determination are presented in Table 2. The collected data were compiled for the year 1998 and used for suitable statistical purposes. The discharge values (in meter cube per second) used in this paper are taken from the United States Geological Survey (USGS)-online maintained database, which provides both real-time and compulsory data. Not all of PVWC and USGS monitored stations matched identically. Therefore, each station described in this paper was associated with the exact or the closest streamflow gaging stations.

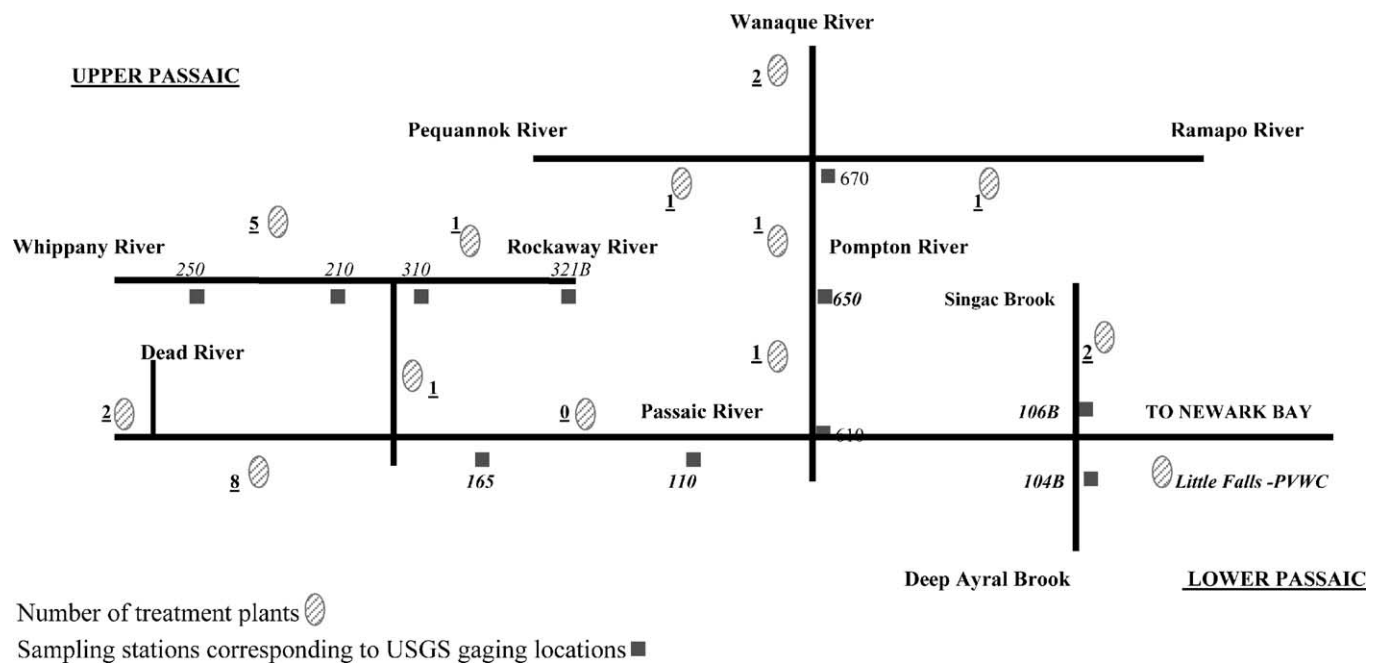


Fig. 1. Sampling locations and USGS gaging locations along Passaic River and its tributaries.

Table 2  
The variables used and their abbreviation, unity, method of determination and origin

Parameter	Abbreviation	Unit	Method	Origin
Hardness	Hard	CaCO <sub>3</sub> , mg/l	SM 2340C	PVWC
Alkalinity	Alkal	CaCO <sub>3</sub> mg/l	SM 2320B	PVWC
Turbidity	Turb	NTU	SM 2130B	PVWC
pH	pH	pH units	SM4500-H <sup>+</sup> B	PVWC
Temperature	T	°C	SM 2550B	PVWC
Odor	Odor	Qualitative	SM207	PVWC
Color	Color	Chloroplatinite	SM 2120B	PVWC
Dissolved oxygen	DO	mg/l	SM 4500-0.G	PVWC
UV254	ULLV254	cm <sup>-1</sup>	SM 5910B	PVWC
SUVA	SULLVA	–	–	PVWC
Nitrite	NO <sub>2</sub>	NO <sub>2</sub> -N, mg/l	SM 300A	PVWC
Nitrate	NO <sub>3</sub>	NO <sub>3</sub> -N, mg/l	SM 300A	PVWC
Ammonia	NH <sub>3</sub>	NH <sub>3</sub> -N, mg/l	SM 4500-NH <sub>3</sub> D	PVWC
Chloride	Cl <sup>-</sup>	mg/l	SM 4500 CIG	PVWC
Biological oxygen demand 5	CBOD5	BOD5, mg/l	SM 5210B	PVWC
Chlorophyll-a	Cl-a	C <sub>a</sub> , mg/l	USEPA 446.D	PVWC
Coliforms	Tcoli	Conn <sup>+</sup> /100 ml	SM 9222 B	PVWC
Total organohalogenes	TOX	µg/l	SM 5320-	PVWC
Heterotrophic plate count	SPC	CFU/ml	SM 9215 B	PVWC
Flow	Flow	M <sup>3</sup> /s	Remote sensing	USGS

PVWC: Passaic Valley Water Commission, USGS: United States Geological Survey.

### 2.3. The multivariate analysis

PCA seeks to establish combinations of variables capable of describing the principal tendencies observed while studying a given matrix. In mathematical terms, PCA relies upon an eigenvector decomposition of the covariance or correlation matrix. Generally, while dealing with environmental data, the distribution among components is relatively well spread-out. The problem is thus to discard, or not, some of the components based on the fact that they are artificially formed by very few items, which moreover already stood out in one or more of the first components. In this study, only factors exhibiting an eigenvalue of over 1 was retained. The correlation matrix was used since the units or the variables are greatly different. Also, a varimax rotation is performed to address the problem of variables loading moderately (or equally) on one or more of the axes. A secure increased PCs chemical/environmental significance is the consequence of this rotation on the interpretation of the results.

After verifying that the data exhibit linear relationships to the dependent variable, different PCA were run using the same data but in differently built databases, in relation with the goal addressed. Indeed, it is acknowledged herein that the statistical power is amplified when different analysis are conducted with the same data, leading to a neat increase of type I errors.

The strategy adopted to analyze the data relying on space and time vectors was as the following:

- (a) First, a “general” analysis concerned the entire database (A).

- (b) Second, aiming to eliminate the impact of external forcing, a “specific” analysis concerned the same database (A), but only the 12 more correlated parameters extracted from the general analysis were taken into account.
- (c) Third, in order to distinguish the trends in the variation of each parameter during a given season, database (A) was divided into four distinctive databases. Winter corresponded to January, February, and March; spring to April, May, and June; summer to July, August, and September; and fall to October, November, and December. Therefore, four “seasonal” separate PCAs were carried out.
- (d) Fourth, the temporal analysis is pursued using a database (B) in which, the measurements from different stations were treated by station and by season independently of the nature of the parameters monitored.
- (e) Fifth, the temporal impact on each station is investigated using four databases built for each season, in which the measurements for each station are treated as they were corresponding to one unique parameter. W100 represents all the data in station 100 in winter (W).

### 3. Results

#### 3.1. Passaic River raw data and water quality trends

The mean, the range, the month of minimal and maximal values, and the number of data collected per parameter and per station throughout the year 1998 are presented in [Table 3](#). A classic way to analyze such a database would be to draw Box plots (also called box-and-whisker plots) of each individual variable in each sampling station. Beside the length of work that it represents, correlations between more than two parameters are not easy to establish at a glance. Thus, for a more comprehensive insight into the studied area, a multivariate analysis is needed to extract the main characteristics of this important set of measurements.

Six leading PCs associated with their empirical orthogonal function (EOF) have been extracted that explain a relatively significant portion of the total data set variance (from 27 to 6.17%, respectively). [Table 4](#) shows the results of the general and specific PCAs with the leading EOF patterns, the corresponding eigenvalues, which are the amount of variance, extracted by each factor, and the variance percentages (accounted for and accumulative) corresponding to the principal components. In fact, discarding the variables that were exhibiting markedly higher scores than the rest of the variables, and then running a second PCA, provided comparable results. Instead of six, five EOFs only were extracted. The main correlations between variables are bolded in [Table 5](#). Alkalinity and hardness (0.94) showed the strongest correlation.

To summarize, the main trends of these two PCAs can be classified now as geological (hardness, alkalinity, chloride ion), bio-chemical (temperature, nutrients, DO, BOD, coliforms and bacteria) and organic (TOC, TOX, UV254).

#### 3.2. Spatial and temporal water quality patterns

The trends and loadings of the four temporal PCAs—one for each season—are presented in [Table 6](#). In winter, EOF1 accounted for 24% of the total variance and represents the

Table 3

Mean values, range, month of minimal and maximal values, and number of data of physical and chemical properties of Passaic River water at sampling locations during 1998

Station	T °C	ph pH units	Turb. NTU	Color Chloro- platinite units	odor	DO mg/l <sup>1</sup>	TOC mg/l <sup>1</sup>	UV254 cm <sup>-1</sup>	Alkal. CaCo3 mg/l-1	Hard CaCo3 mg/l <sup>1</sup>	NO <sub>2</sub> NO <sub>2</sub> -N mg/l <sup>1</sup>	NO <sub>3</sub> NO <sub>3</sub> -N mg/l <sup>1</sup>	NH <sub>3</sub> NH <sub>3</sub> -N mg/l <sup>1</sup>	Cl mg/l <sup>1</sup>	BOD BOD5 mg/l <sup>1</sup>	Cl-A Ca <sub>o</sub> mg/l <sup>1</sup>	T Coli. Conn+/ 100ml	SPC CFU/ml	TOX ug/l <sup>1</sup>
100	14.66	7.37	7.74	46.58	2.91	9.67	4.94	0.11	67.16	112	0.037	2.74	0.12	80.53	4.21	23.09	1291	3168	58.68
	3.88-24.4	6.8-7.8	2.5-12.2	24-76	2.0-3.0	8.6-11.9	3.76-6.13	.082-.136	32-96	34-162	.006-.1	.297-5.9	.034-0.7	38-113	2.82-5.9	2.47-56.6	400-2200	130-19500	15.2-265.6
	02-08	03-08	11-06	12-04	Lv	06-02	09-11	10-04	05-12	05-12	Lv	05-10	07-01	05-11	04-06	05-M	02-07	02-07	05-09
	12	12	12	12	12	12	8	12	12	12	12	12	12	11	8	12	12	12	9
104	9.74	7.37	7.03	50.5	2.5	7.825	6.75	0.166	104.1	168.2	0.037	0.825	0.264	77.36	4.5	5.7	1034	3670	157.43
	4-23.3	7.1-7.8	2.6-17.3	32-85	1.0-3.0	5.32-10.5	4.44-11.36	.076-.322	52-136	71-238	.006-.1	.08-1.42	.04-2.00	18.8-107.4	1.66-6.93	.1-19.54	410-2400	150-17200	19.5-345.7
	02-08	12-09	11-08	10-03	Lv	08-12	06-08	12-08	05-12	05-11	Lv	07-02	09-11	05-11	06-08	03-M	02-07	01-10	05-01
	12	12	12	12	12	12	8	12	12	12	12	12	12	11	8	12	12	12	9
106B	11.42	7.32	3.53	31.2	2.5	9	5.56	0.11	81	157.7	0.037	7.64	0.19	90	3.7	9.53	1085	10306	126.7
	-13-23.8	7.0-7.8	.74-10.4	15-74	2.0-3.0	6.6-10.7	3.9-7.6	.072-.238	56-110	84-188	.006-.1	4.1-12.5	.06-1.52	36.7-125.5	2.2-6	1.92-28.3	240-2100	150-100800	37.7-277.6
	02-08	03-10	11-08	10-03	Lv	08-12	09-05	02-08	05-07	05-02	Lv	05-10	09-07	05-11	06-07	05-M	02-06	02-07	05-01
	11	12	12	12	12	12	8	12	12	12	12	12	12	11	8	11	12	12	9
110	11.92	7.45	7.67	45.16	2.25	16.93	5.87	0.139	77.5	134	0.037	3.58	0.127	84.9	3.83	5.98	551.66	5925	81.74
	-14-25.5	6.8-7.7	1.8-15.8	22-64	1.0-3.0	6.6-103.8	4.226-9.65	.088-.28	40-110	66-192	.006-.1	.37-6.9	.05-133	30.35-137	2.28-5.43	1.15-23.4	100-900	300-54400	18.3-274.8
	02-08	01-11	11-06	10-03	Lv	04-03	08-05	10-05	04-10	04-11	Lv	04-11	09-01	05-11	09-01	01-M	02-03	04-07	04-01
	12	12	12	12	12	12	8	12	12	12	12	12	12	11	8	12	12	12	9
165	14.16	7.5	6.92	57	2.5	8.69	6.48	0.22	66.5	110.75	0.1	2.65	0.165	76.44	4.17	651.8	3475	3170	50.22
	3.3-24.4	7.3-7.6	6.6-7.5	25-98	2.0-3.0	7.2-10.05	5.8-8.66	.108-.345	44-84	66-154	<.006-.1	.4-6.3	.09-.286	29.3-140	3.66-4.61	.11-2600	300-11500	250-9000	31.5-82.3
	M	04-10	03-01	11-04	Lv	08-01	11-01	10-04	04-10	04-10	Lv	04-10	01-04	05-10	07-04	01-07	M-07	M-07	04-01
	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
210	11.52	7.49	6.03	39.3	2	8.83	5.1	0.14	85.3	142.2	0.006	2.08	0.21	78.34	3.3	6.1	858	5554	38.88
	-15-23.8	7.1-7.8	2.2-11.6	22-64	2.0-3.0	5.4-12.78	3.6-11.1	.06-.36	56-110	66-198	.006-.1	.16-3.57	.06-.25	24.6-104	2.82-5.7	2.18-25	100-1300	100-44800	5-98.3
	02-08	04-09	11-03	11-04	Lv	05-12	09-05	12-05	05-10	03-11	Lv	05-10	09-05	05-10	09-04	02-M	02-07	02-07	04-01
	12	12	12	12	12	12	8	12	12	12	12	12	12	11	8	12	12	12	9
250	14.71	7.72	2.95	30.25	3	9.81	3.54	0.096	75.5	130	0.068	1.62	0.165	74.26	3.35	352.4	20525	2617	64.57
	7.2-23.8	7.5-8	1.9-4	25-38	3	7.3-11.5	3-4.3	.062-.135	56-100	100-167	.006-.1	1.2-2.4	.065-.26	61.8-88.2	2.6-4	1.1-1400	600-80000	110-7300	8.4-97.5
	M	01-10	01-07	11-03	Lv	07-01	07-01	13-04	04-12	04-10	Lv	10-04	10-07	04-10	04-07	M-07	M-07	M-07	04-01
	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3

Table 3 (Continued)

Station	T °C	ph pH units	Turb. NTU	Color Chloro- platinite units	odor	DO mg/l	TOC mg/l	UV254 cm <sup>-1</sup>	Alkal. CaCo3 mg/l	Hard CaCo3 mg/l	NO <sub>2</sub> -N mg/l	NO <sub>3</sub> -N mg/l	NH <sub>3</sub> -N mg/l	Cl mg/l	BOD BOD5 mg/l	Cl-A C <sub>10</sub> mg/l	T Coli. Conn+/ 100ml	SPC CFU/ml	TOX ug/l
<b>310</b>	12.02	7.55	2.96	32.75	2.33	9	5.45	0.12	72.41	114	0.037	3.7	0.077	64	3.61	29.1	903.33	3231.66	86.49
	-14-23.8	7.2-7.8	.95-8.6	23-54	1.0-3.0	5.6-11.88	4.2-6	.08-.16	40-102	64-161	.006-.1	.4-7.3	.04-.244	28-92.2	2.12-7.83	1.07-119	40-1800	90-18000	13.7-176.1
	02-08	12-06	11-08	11-05	Lv	08-02	07-01	02-08	05-09	03-12	Lv	05-12	02-04	05-12	04-01	05-M	02-08	03-07	04-01
	12	12	12	12	12	12	8	12	12	12	12	12	12	12	11	8	12	12	9
<b>321B</b>	11.76	7.33	2.1	17.41	2	9.2	2.95	0.06	144	200	0.006	1.055	0.146	72.33	2.7	14.11	1134	2256	17.61
	-12-21.1	7-7.5	1-3.2	30-Jul	2.0-3.0	7.3-11.8	1.95-5	.04-.1	130-171	172-256	.006-.1	.74-1.38	.06-.142	61.7-87.25	1.64-6.5	4-56.8	400-3100	70-10300	26-28.3
	03-08	12-07	11-08	11-06	Lv	08-02	07-01	07-01	08-01	05-02	Lv	02-08	09-12	07-01	10-01	05-M	10-07	02-07	10-08
	12	12	12	12	12	12	8	12	12	12	12	12	12	12	11	7	12	12	9
<b>610</b>	11	7.6	7.4	34.58	2	10	4.02	0.09	61.25	99.58	0.037	1.84	0.094	63.2	4	7.63	795	3016	29.43
	-14.5-25	7.2-7.9	Feb-35	20-56	2.0-3.0	7.7-12.22	3.2-5.2	.06-.13	34-100	45-192	.006-.1	.57-6.9	.02-.32	22.2-128	2.44-6	1.0-13.35	300-1900	20-15000	10.1-55.1
	02-08	01-08	11-08	02-09	Lv	08-12	08-11	02-05	05-11	05-12	Lv	05-12	09-04	05-12	02-10	03-M	01-05	02-07	05-11
	11	12	12	12	12	12	8	12	12	12	12	12	12	12	11	9	12	12	9
<b>612</b>	10.64	7.56	7.4	36.5	2.5	10.01	3.93	0.088	58.91	94.04	0.037	0.76	0.132	56	4.74	6.08	712.5	2929	20.12
	-15.6-25	6.9-8.1	2.1-29	21-64	2.0-3.0	7.1-12	3.2-4.6	.064-.134	46-82	50-135	.006-.1	.002-1.9	054-.15	22.5-82.6	2.31-7.25	2.88-13.8	300-1850	140-16300	6.4-55.75
	02-08	01-09	01-08	03-09	Lv	08-12	09-06	02-05	05-12	05-12	Lv	10-12	08-11	05-02	06-04	03-M	06-05	02-07	09-11
	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
<b>650</b>	10.88	14.05	6.38	33.72	2.4	9.46	3.87	0.085	55.8	87.4	0.076	0.8378	0.072	47.68	4.532	215.4	3090	1559	13.52
	-14.5-24	6.6-7.8	1.4-7.9	25-50	2.0-3.0	7.7-11.44	3.36-5.16	.058-.13	32-72	55-127	.006-.1	.1-1.9	.03-.121	1.2-82.6	2.3-8.1	1.55-88.5	400-24000	140-4700	.89-24.7
	M	01-10	12-08	12-09	Lv	09-12	09-08	12-04	04-12	04-12	Lv	05-12	09-07	07-12	07-04	06-07	11-07	01-10	09-10
	8	10	10	10	10	10	9	10	10	10	10	10	9	10	9	9	10	9	9

Lv: low variability to distinguish a minimum and a maximum, M: missing data (no sampling at a given period).



Table 4  
PCA results on Passaic River data during 1998

PCA with 20 variables				PCA with 12 variables			
EOF	Factor	Loadings	Total variance (%)	EOF	Factor	Loadings	Total variance (%)
5.41	Hardness	0.92	27.07	4.06	NH <sub>3</sub>	−0.82	33.85
	Alkalinity	0.87			Cl <sup>−</sup>	0.7	
	Cl <sup>−</sup>	0.3					
	pH	0.29					
3.08	<i>T</i>	0.84	15.42	1.76	<i>T</i>	0.92	14.69
	NO <sub>2</sub>	−0.89			NO <sub>2</sub>	−0.86	
2.32	Cl <sup>−</sup>	0.9	11.61	1.5	Hardness	0.93	12.46
	NH <sub>3</sub>	−0.81			Alkalinity	0.93	
	BOD	−0.78					
2.15	TOC	0.84	10.75	1.21	Odor	0.88	10.11
	TOX	0.73					
1.34	Odor	0.75	6.74	1.03	TOX	0.95	8.62
1.23	Cl-a	0.74	6.17				
	pH	0.59					
	UV254	−0.65					

EOF: empirical orthogonal factor.

gradient of chemical and organoleptic parameters (turbidity, UV254, and color) which all lied in the negative region. EOF2 accounted for 20% of the total variance and mainly represents the seasonal impact of the water temperature. In the spring, EOF1, with 32% of the total variance, was directly linked to the solute content (Hardness, Alkalinity, Cl<sup>−</sup> ion) and organic pollution (TOX). This component represents the fluctuation of the discharge along the river with the land washing process due to snow melting and heavy rain. In the summer, the classical signs of eutrophication composed the extracted components. In the fall, TOC and UV254 were the factors that were strongly correlated showing together 26% of the total variance, followed by the solute content, 16.6%. This is the sign of either a lack of dilution or heavy loaded non-point source pollution.

The spatial PCA, in which data were compiled by station, showed a neat separation into two groups. As seen in Fig. 2A, all the stations were aligned along factor 1 except stations 106B and 321B, which were aligned with factor 2 and opposed in signs. Thus, all stations seemed to face the same phenomena during the studied period with a particular situation in both 106B on Deep Ayril Brook and 321B on upstream Rockaway River siege of a suspected non-point source of pollution.

The spatio-temporal PCA, in which all the stations were represented in four seasons (i.e. station 100 represented as W100, G100, S100, and F100 for winter, spring, summer, and fall, respectively), gave three groups of stations-seasons, as seen in Fig. 2B. In fact, only the two side groups—closer to the principal components 1 and 2—were the ones of interest. The first principal component, accounted for 24% of the total variance, contained all the winter stations and all the fall stations except F610 and F650. The second principal component, with 19.3% of the total variance, contained all spring stations except G321B.



Table 6  
Temporal PCA results on Passaic River during 1998

Winter				Spring				Summer				Fall			
EOF	Factor	Loadings	Total variance (%)	EOF	Factor	Loadings	Total variance (%)	EOF	Factor	Loadings	Total variance (%)	EOF	Factor	Loadings	Total variance (%)
4.74	Turb	-0.76	23.73	6.45	Alkal	-0.91	32.26	5.19	<i>T</i>	-0.7	25.98	5	TOC	0.9	26.35
	Color	-0.93			Hard	-0.96			Turb	-0.87			UV254	0.871	
	UV254	-0.89			Cl <sup>-</sup>	-0.91			Color	-0.75					
					TOX	-0.71			Alkal	0.87					
									Hard	0.86					
									BOD	-0.71					
4.06	<i>T</i>	0.79	20.31	3.31	DO	0.88	16.57	4.65	TOC	0.91	23.26	3.16	Alkal	0.94	16.64
	Alkal	0.84			TOC	-0.75			UV254	0.95			Hard	0.9	
	Hard	0.72			UV254	-0.77			NH3	0.72					
2.75	BOD	0.86	13.75	1.96	NO <sub>2</sub>	-0.82	9.83	2.33	NO <sub>2</sub>	0.84	11.64	2.68	NO <sub>3</sub>	-0.8	14.14
1.78	NO <sub>3</sub>	0.77	8.93	1.73	<i>T</i>	-0.76	8.68	1.67	Cl-a	0.77	8.37	1.98	SPC	0.88	10.44
	TOX	0.75			Cl-a	-0.8			SPC	0.7					

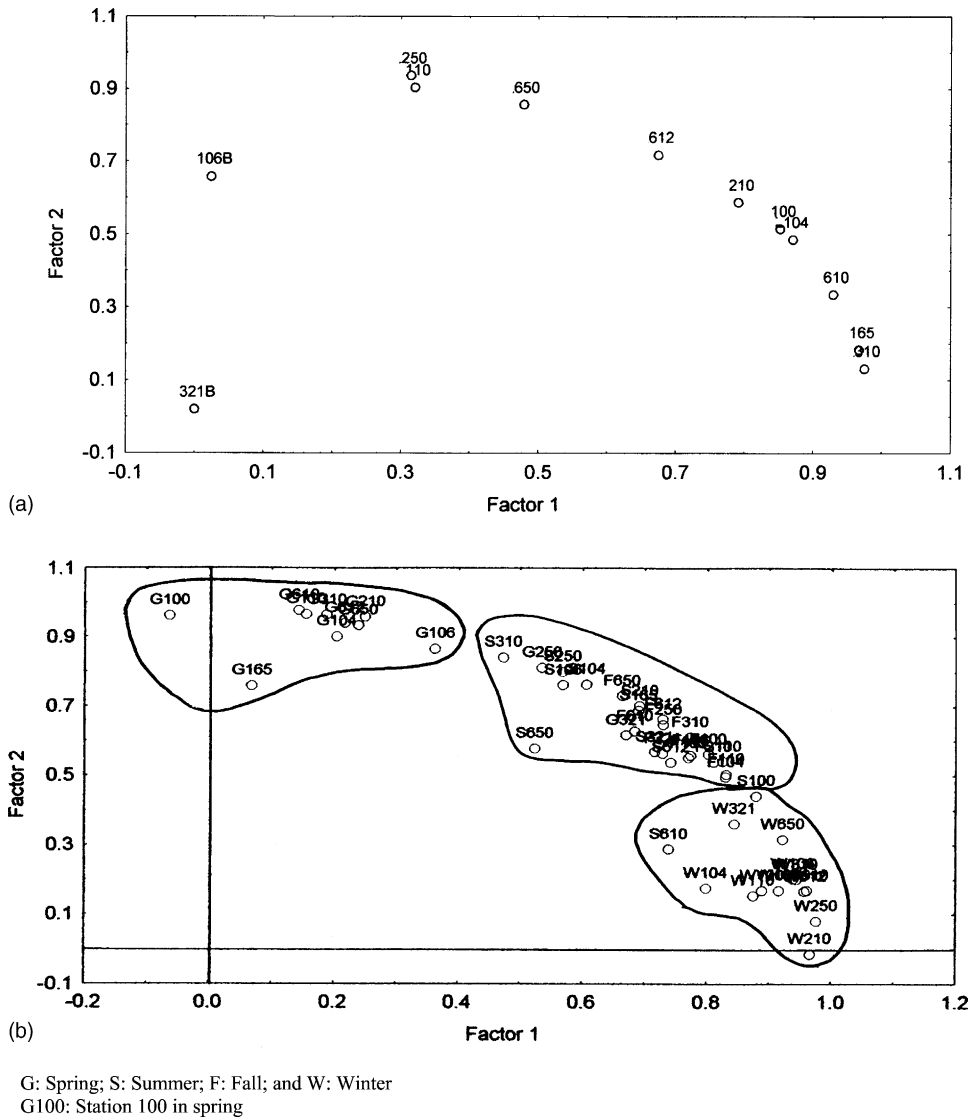


Fig. 2. Spatio-temporal segregation of the stations during 1998.

Some stations were also correlated to the second group as F650, and summer stations of downstream upper Passaic, Rockaway, Whippany, and upstream Pompton, which still is the receptacle of Pequannock, Wanaque, and Ramapo Rivers. The correlations between the fall stations were very strong, all above 0.990 as well as the one between G310 and G110, between F321 and G310, and between S321 and G321. Here again, the fall season induced a common and strong pattern to all the stations along Passaic River. The weakest correlations ( $r < 0.4$ ) corresponded to all the spring stations except G250, G321, and G310.

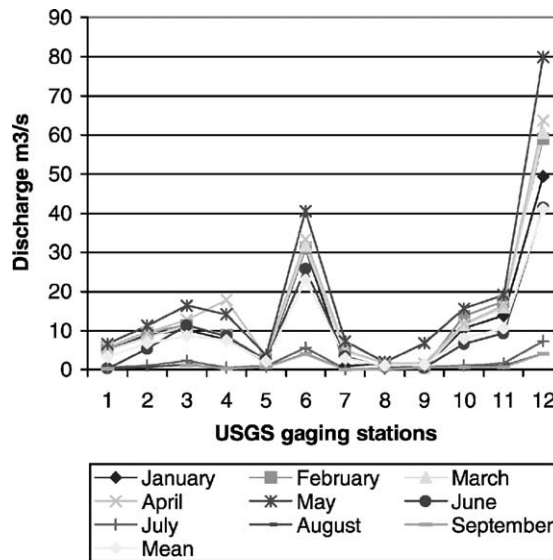
To summarize, a temporal segregation of the station was possible. During winter and fall, all the stations shared the phenomena that occurred during these two seasons. These phenomena could be an extreme stress as snow, flood, or dryness. Spring was showing an isolated behavior. It is indeed the snow melting and its consequences: a peak of urban and land runoff, with chloride ion and organic compounds but in highly diluted concentration. Also, the sampling stations seemed to be characterized by their immediate environment as urban, forest or land farming, industrial, municipal or private sewage.

#### 4. Discussion

These results showed clear variations in solute content in Passaic River during the studied period. That evolution is to be related to both conservative and non-conservative parameters. Conservative parameters are chemical parameters, such as alkalinity, hardness, chloride, pH, and many others, that are controlling or resulting of the mineralization processes originated by the lithological composition of the watershed. Non-conservative parameters design all the parameters whose concentrations depend on local conditions [9]. Generally, the conservative parameters follow the same path from up- to down-stream each tributary. An increase of these parameters was noticed, which is consistent with the general behavior of solute in rivers. However, Rockaway River showed a reversed situation. The solute content decreased from up- to down-stream. Undeniably, the geochemical nature of the drainage basin, strongly influence the composition of waters of small streams, therefore inducing individuality, sometimes considerable, within a watershed. Yet, alkalinity, hardness, turbidity, nutrients and organic compound concentrations in small stream, as Passaic River, are strongly dependent over the discharge (flow). At this point, it was necessary to associate the discharge and the climate evolutions. Indeed, a major climatic event affected the stream quantity and quality of Passaic River, as well as other streams throughout the State, during the studied period. In October, November, and December 1998 the average rainfall amounts were 76, 35, and 38 percent of normal, respectively (Northeast Climate Center of Cornell University). Yet, this dry period followed a severely dry summer in which water temperature reaches 25.5 °C (maximum value at station 110). Summer and fall were dry enough to influence the alkalinity and hardness in the river. The opposition of signs obtained for the main patterns (EOF1 and 2) are reflecting a specific situation. In the spring, season in which the snow melting induces a considerable stress, increasing the dilution but also the chloride ion and urban and land runoff that is represented here by TOX, TOC, and UV254. In fall and winter, the EOF1 was organic oriented. Because of the lack of dilution, summer showed some disturbances on different parameters that were above normal. This situation stayed unchanged in the fall but the organic parameters also reached extreme values. Nitrate and nitrite higher values come from a ground water discharge rather from overland flow. If monitored, phosphate instead would have showed a neat decrease during the fall because its strong dependent of the urban and land runoff.

There were indeed seasonal differences in terms of solute content. This factor was opposed to the organic contents in all PCAs, and with different signs: positively, in spring and summer, and negatively in fall and winter. However, spring and winter showed a strong influence of solute content, both in EOF1. The minimum of conservative parameters was

registered on all station between March and May, and the maximum between September and December. This is directly linked to the flows along the river, thus the discharge. The Table 7 shows the mean annual discharges ranges and for the studied period of the streamflow-gaging stations in operation in the year 1998 that correspond or are closely associated to PVWC monitored stations. Mean annual discharges in cubic meter per second per square kilometer is the average number of cubic meter of water flowing per second from each square kilometer of area drained, if runoff is assumed to be distributed uniformly in time and area [10]. Some of the results might be disturbing but natural hydrologic condition or man-made conditions might affect the discharge at a given station. Man-made conditions are structures as dam, channels, or streamflow diversions, groundwater withdrawals adjacent to streams that all influence the discharge on a more or less long-term. Discharge along Passaic River is regulated through dams and natural water retention installation as lakes or ponds. Nevertheless, the evolution of the monthly discharge between January 1st and September 31st is showed in Fig. 3. Droughts occurred at least twice that year. July and September showed critical values and actually, the drought period extended to December. According to



#### Closest sampling stations

- 1,2: Upper Passaic close to Dead River (station 165)
- 3,4: Rockaway River (station 321B)
- 5: Whippany River at Morrision (station 250)
- 6: Passaic River at Pine Brook, NJ (stations 210 and 310)
- 7: Pequannock River at Macopin intake dam
- 8: Ringwood Creek near Wanaque
- 9: Wanaque River at Wanaque
- 10: Ramapo River near Mahwah
- 11: Ramapo River at Pompton Lakes (station 650)
- 12: Passaic River at Little Falls (station 100)

Fig. 3. Monthly evolution of the discharge during 1998.

Table 7  
Variation of Passaic watershed streamflow-gaging stations in 1998 (calculated from USGS, 2001)

USGS gaging stations	Drainage area (km <sup>2</sup> )	Mean annual (m <sup>3</sup> /s)	Lowest annual mean (m <sup>3</sup> /s)	Highest annual mean (m <sup>3</sup> /s)	Mean annual m <sup>3</sup> /(s km <sup>2</sup> )	Remarks <sup>a</sup>
1379000 (165)	141.02	3.30	0.37 (1965)	1.54 (1952)	42.73	
1379500 (165)	256	6.83	1.91 (1965)	8.63 (1984)	37.48	
1380500 (321B)	296.96	8.65	2.49 (1965)	11.21 (1952)	34.33	Discharge regulated by Splitrock reservoir
1381000 (321B)	304.64	7.47	1.46 (1965)	8.37 (1952)	40.78	Discharge regulated by Boonton and Splitrock reservoirs. Water diversion for Jersey City water supply
1381500 (250)	75.26	2.16	0.66 (1965)	2.78 (1984)	34.84	Discharge occasionally regulated by operation of gates at Pocahontas Dam
1381900 (110)	893.44	23.10	7.81 (1981)	18.11 (1984)	38.67	Discharge regulated by Boonton and Splitrock reservoirs and many small lakes. Water diversion for Jersey City water supply
1382500 (670)	16307	2.91	0.003 (1954)	3.08 (1952)	56.03	Discharge regulated by Canistear, Oak Ridge, Clinton, and Charlotteburg reservoirs and Echo Lakes. Water diversion for City of Newark municipal water supply
1384500 (670)	48.9	1.08	0.37 (1965)	1.54 (1952)	45.27	Discharge slightly regulated by lakes upstream
1387000 (650)	232.41	1.34	0.05 (1966)	6.53 (1920)	173.44	Discharge regulated by Greenwood lake, Monksville and Wanaque reservoirs. Water diverted by North Jersey District Water Supply Commission for municipal supply
1387500 (670)	307.56	8.02	2.81 (1985)	13.05 (1903)	38.35	Discharge affected by groundwater diversions and regulated by Lakes and ponds upstream
1388000 (670)	409.6	10.60	2.06 (1985)	14.49 (1984)	38.64	Regulation by Pompton Lake. Discharge regulated by Canistear, Oak Ridge, Clinton, Monksville, Charlotteburg, Wanaque reservoirs and Greenwood and Echo Lakes.
1389500 (100)	1950.72	41.04	7.61 (1965)	67.77 (1903)	47.53	Discharge affected by diversions upstream Discharge affected by diversion for municipal supply and regulated by reservoirs upstream

The number in parenthesis in the first column represents the name of the closest sampling station in Fig. 1.

<sup>a</sup> See [24].

the Northeast Regional Climate Center of Cornell University, the average rainfall amounts in percent of normal were 76, 35, and 38 for October, November, and December. Therefore, it is clearly understand now the reason for which the solute content was permanently under pressure and appeared at all PCAs, as well as the organic parameters group that were in opposition. Comparing the annual mean discharge values compiled in Table 7 did not help, in this case, understanding the reality of the situation of the watershed. The reality has been partially biased because the discharge is controlled throughout the watershed streams.

## 5. Conclusion

1. This study covered a 1-year-period monitoring in which Passaic River watershed faced two drought stresses.
2. The results showed the impact of organic, biological, and chemical patterns. PCA results, monthly mean discharges, and annual mean discharges were used to explain the opposed patterns obtained. These extracted patterns were of natural, urban, industrial, and agricultural origins. During the drought stresses, the organic parameters were the most strongly correlated.
3. It was possible to isolate stations showing a particular behavior or a sign of a possible point or non-point source of pollution. Monitoring programs are essential in assessing temporal and spatial source water quality.
4. This study showed that any collected monitoring information can be used and is of crucial importance, especially for planning purposes (e.g. plants improvements, new highways, roads, and bridges for instance). It also verified that it is in the interest of the water purveyor to know the quality evolution of the source water. This can be done only through monitoring.

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