Hydrochemical Interpretation of Stormwater Impact on Groundwater using Factor Analysis

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Abstract

Groundwater samples were collected from both open and bore wells over 591 km^2 of Karachi, Pakistan pre- and post-monsoon 2007. The samples were analyzed for the trace metals copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn), and iron (Fe) and conductivity to ascertain the impact of stormwater on the groundwater quality of three basins—Lyari, Hub, and Malir. The data were subjected to R-mode factor analysis and the scores were transferred to maps. The results show that Pb and Zn are most abundant in all three basins as a result of stormwater infiltration into groundwater.

Keywords: Stormwater, factor score, contamination, basin, Karachi.

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1. Introduction

Hydraulic connections to stormwater infiltration are based on groundwater hydrology, soil water characteristics, groundwater flow direction, permeability of vadose and saturated zones, and water table depth. Hence the interactive relationship of water chemistry with hydrological and geological environments is used to explain the levels of solubility of certain trace metals in groundwater. Statistical analysis can be applied to measure variables to identify a number of factors, such as pollution, for quantification. The spatial distributions of different possible sources and parameters have different chemical signatures. The signatures identify factors through R-mode analysis, location of possible sources, and by contouring the factor scores [1]. Factor analysis has been widely used for hydrochemical interpretation of groundwater data [2]. It has a threefold advantage over normal techniques [3-5]. This advantage includes data reduction, dimensionless quantities, consideration of smaller and larger ions with equal emphasis, and quantitative measurement of the importance of each actual effect or pollution source on the observed parameter values. In evaluating the suitability of an infiltration basin, groundwater hydrology plays an important role in determining the chemical constituents present in stormwater that are not removed in the soil underlying the infiltration basin. A hydraulic connection between the surface water and the infiltration basin means that the constituents of the infiltrated stormwater runoff passing through the soil in elevated concentrations adversely impact aquatic life in the groundwater discharge environment. The effect of trace metals in stormwater discharge on groundwater would increase not only for the groundwater receiving the polluted stormwater, but also for the polluted waters that enter water bodies. In the present study, factor analysis is used to interpret the impact of stormwater on the groundwater quality of three basins in Karachi, Pakistan—Lyari, Hub, and Malir rivers. R-mode factor analysis with varimax rotation technique is applied using the standard program of Davis [6].

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2. Material and Methods

A survey was conducted to establish the quality of the groundwater through which stormwater infiltrates the detention basin. Three detention basins were selected for the study. These basins differ in surface area, depth, and number of sampling points but have similar soil covers comprised of sand, silt and gravel and drain stormwater from commercial, residential, agricultural, and public properties. All the sampling points are close to the basin and toward the hydraulically downgradient end, as determined from groundwater gradient and topographic maps, in an attempt to increase the probability that the groundwater samples would be representative of the effect of stormwater entering and infiltrating through the basins. All 66 groundwater samples from 33 bore holes/wells were collected pre- and post-monsoon 2007 (Figure 1).

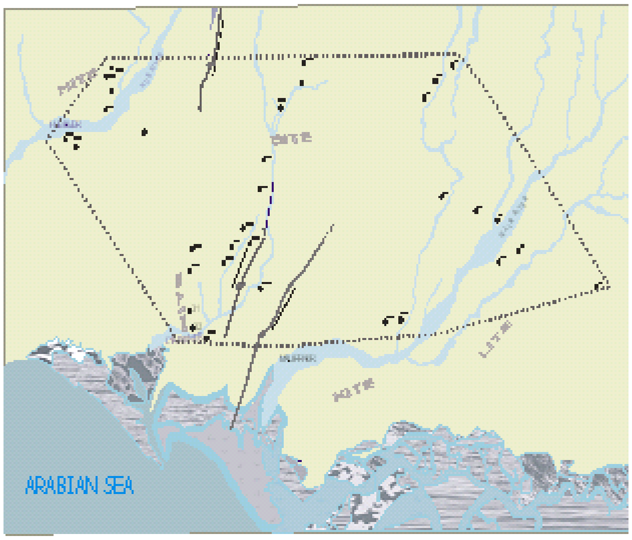

Figure. 1 Map showing sampling points basins and industrial sites of the study area.

Water quality has been monitored seasonally i.e., pre- and post-monsoon season, and has been analyzed for trace metals such as copper (Cu), cadmium (Cd), lead (Pb), iron (Fe), zinc (Zn), and conductivity. In general, rainfall tends to be the main source of subsurface water recharge. Rainfall in the city is around 200 mm per year based on a record of the last 50 years [7] and the average monthly temperature ranges between 25 and 37^{o} C [7]. The city receives an average annual precipitation of 200 mm and has an arid coastal climate. The low precipitation rainfall accounts for a small fraction of the total recharge, i.e., 1.9 x 10^{6} m^{3}/yr [8]. Each water sample was collected in such a manner that it would not deteriorate or be contaminated with any other substance. It was sampled from the bore holes/wells only when the bore holes/wells were pumped sufficiently long enough to ensure that pH, temperature, and specific conductivity had stabilized, and the samples represented the groundwater of the aquifer. Samples collected from the same basins during the monitoring period in 2007 (pre- and post-monsoon) were used for comparison to identify seasonal effect, such as evidence of infiltration of stormwater on groundwater quality with respect to trace metals. The United States Environmental Protection Agency's (US EPA's) standard methods for water and wastewater examination were used for determination of the trace metals Cu, Cd, Pb, Fe, and Zn. These elements were analyzed through atomic absorption and spectrophotometer. While performing the analysis two sets of internal standards were run, one at beginning and other in between analyses, to check the accuracy and precision of the results [9]. For most of the elements, the detection limits were around 1 mg ml^{-1}. A standard method of R-mode factor analysis was followed for this study [2].

3. Study Area

Karachi is a metropolitan city in Pakistan. It is located northwest of the Indus River Delta along the north Arabian Sea (Figure 2).

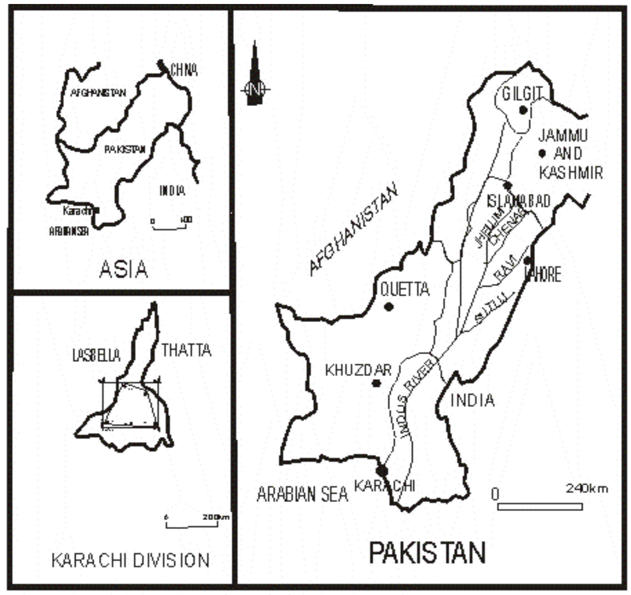

Figure 2. Location map of the study area.

The metropolitan population has grown to over 16.5 million in an area of 3,285 km^{2}. Most of the population is concentrated within the urban area of the city encompassing an area of about 591 km^{2} [10]. Three major water ways, the Hub, Lyari, and Malir rivers, pass the metropolitan city and confluence at the Arabian Sea. These water ways drain stormwater during the monsoon season. Physiographically, the study area falls within two major physiographic regions of Pakistan, namely the Western Highlands and Lower Indus Plain [11]. It is almost bounded by the Hub River in the west and the Malir River basin in the east. To the north, hilly terrain merges into the higher hills and mountains forming the Kohistan range where, as in the south, it is bounded by the Arabian Sea into which the rocky headlands are extended forming capes separated by sandy beaches. In the southeast, the coastal line is characterized by a coastal cliff and development of creeks. Elevations in the study area generally range between 50 m in the north and 14 m in south. The bedrock material filling the Karachi embayment comprises marine and estuarine sediments of considerable thickness with subordinate lacustrine and lagoonal deposits. Geologically younger deposits are mainly fluvial and aeoline, composed of conglomerates, consolidated and semi-consolidated gravels, and incoherent loess deposits in places. Geomorphic evaluation and morophostructural analyses suggest that non-tectonic activity during the quaternary period resulted in marine regression [12]. The quaternary deposits are the only lithological units spread over most of the study area. These consist of gravel beds and alluvial deposits. The thickness of the alluvial deposits increases towards the northwest and ranges between 30 and 50 m.

4. Results and Discussion

Scientifically, pollution can be defined as anomalous distribution and accumulation of elements and other undesirable compounds in air, land, and water, which affect the survival of living organisms and degrade the environment. It has become very important to identify the possible environmental pathways of several toxic trace elements and to understand their migration in hydrological systems in order to control them. Ashley and Leoyd [13] applied the factor analysis technique to identify the hydrological process in the Santiago basin of Chile Lawrance. Upchurch [14] used this technique to outline the zones of natural recharge to groundwater in the Floridan aquifer. Factor analysis techniques have also been used to describe the pollution in highly industrialized zones [15-17]. The study of the above workers suggests that by applying factor analysis, data could be regrouped into a few independent factors explaining the intensity of performance. In the Hub, Lyari, and Malir basins of Karachi, trace metals such as Cu, Cd, Zn, Pb, and Fe are entering groundwater with stormwater, enhancing the level of pollution of these basins.

4.1. Hub Basin

The isoconductivity of the area when compared shows moderate contamination during the post-monsoon period versus pre monsoon (Tables 1a-b); however, high conductivity water surrounded the effluent channel prior to monsoon season (Tables 2a-b). The conductivity of the groundwater decreases as distance from the basin increases in both monitoring periods. The first three factors of the data set (pre- and post-monsoon) can explain 90% of the total variance. The factor scores are tabulated in Tables 1c-d and shown in Figures 3a-b. Factor 1, which includes Cd and Pb, explains 59.1% of the total variance prior to and 44.8% after monsoon season. The zone surrounding the basin prevails a moderate rotated factor score (< 1) in both seasons (Tables 1c-d). Data show (factor 1) negative impact before monsoon and positive loading post-monsoon (Tables 1a-b), suggesting that Cu and Zn are induced into groundwater as a result of waste material collected near the physiographic depression above the groundwater table during the pre-monsoon period. The flushing effect of rain is visible, and is responsible for the infiltration of these

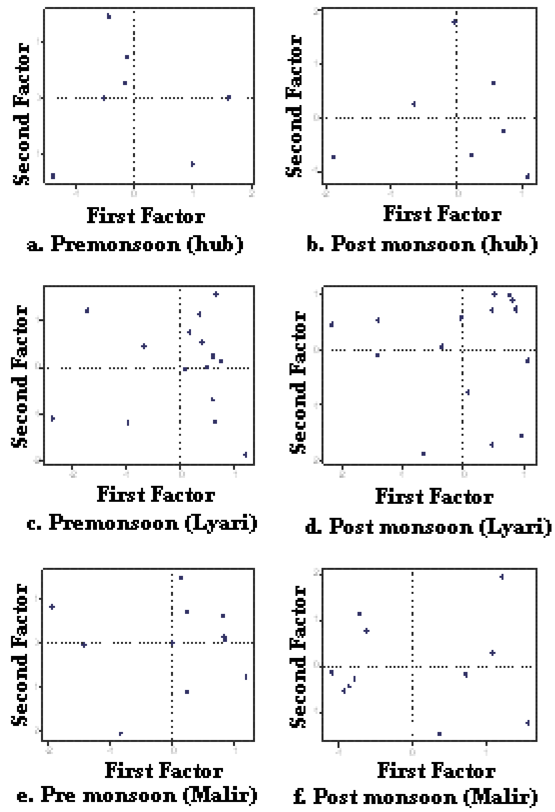

Fig. 3: Distribution Factor Scores

contaminants post-monsoon [2]. Moderate rotated factor loading prevails for Fe pre-monsoon and negative loading post-monsoon, suggesting low mobility and heavy metals co-precipitation during the formation of Ferric Hydro oxide [18], as Fe is unstable and induces low dissolved oxidation in low dissolved oxygen concentrations resulting in very little percolation of Fe from surface to groundwater. The conductivity variance of the area shows moderate contamination of groundwater from stormwater infiltration (Table 1). Table 1 shows relatively moderate conductivity persisting in the water surrounding the basin. The conductivity of groundwater decreases as the distance from the basin increases (Figures 4a-b). The three factors can explain 90% of the data set. The factor loadings and rotated factor scores (varimax) are mentioned in Table 1. The aerial distribution factor scores for both monitoring periods are shown in Figures 3a-b. The impact of factor score on the area is more or less the same during both monitoring periods. A higher score prevails in the up-gradient area and the negative score shown in the low gradient area suggests higher contamination persisting in the up-gradient area. The central zone is unaffected by metal contamination. Factor 2, which include Pb and Fe.

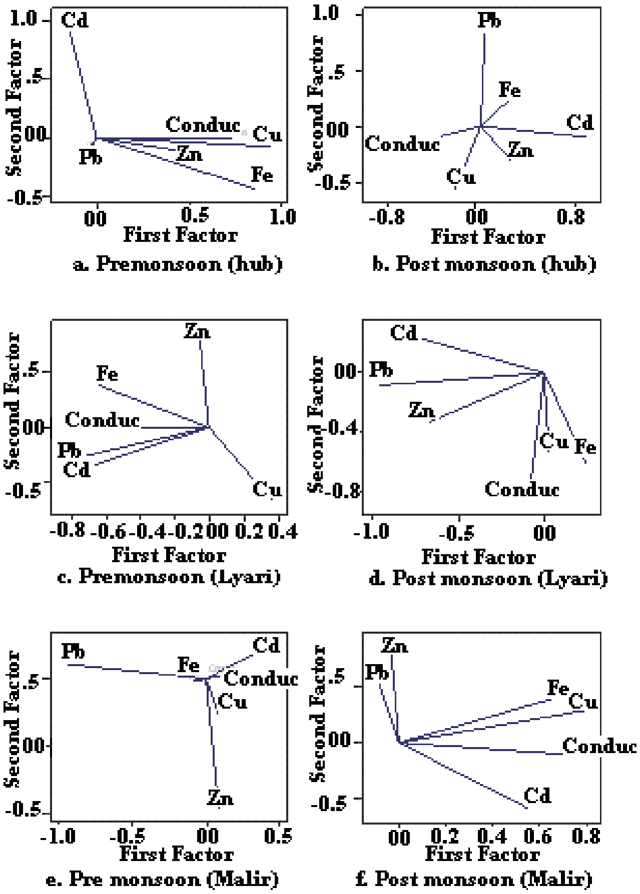

Fig. 4: Component Factor Loading

explains 23.5% of the total variance before monsoon, and 33.8% after monsoon, including Cd and Zn (Tables 1a-b). The distribution of a rotated factor score well above 0.5 suggests that moderate enrichment of Cd and Zn is taking place because of industrial effluent discharge post-monsoon induced into the basin as shown in Tables 1c-d. Similar behavior is not observed pre-monsoon. This demonstrates that the infiltration of Cd and Zn has taken place due to the influence of factor 1. This also reveals that the location affected by factor 1 is not affected by factor 2. Whereas factor 2 has little or no impact on certain wells. The wells at the monitoring location with a low score for factor 2 can be deemed uncontaminated. Negative or zero factor score shows no or negative impact. Factor 3, which explains about 11.5% of the total variance during both monitoring periods, has a negative loading for most of the contaminants. The distribution of factor scores is shown in Figures 3a-b. The high negative score for Fe in this zone is due to dilution and precipitation of Fe as iron hydroxide post-monsoon [19]. Thus the factor analysis delineates the zones affected by different chemical processes. The effluent affects groundwater, which in turn is affected by stormwater and is characterized by a high Cu concentration as suggested by factor 1. The moderate contaminated zone subjected to industrial effluent input into the basin is characterized by Zn and Cd by the influence of factor 1 on factor 2. The groundwater is not affected by factor 3 as suggested by factor scores.

4.2 Lyari Basin

The factor loading map of Lyari Basin post-monsoon shows no contamination of groundwater by stormwater infiltration. However, a mild impact is indicated during pre-monsoon season due to industrial input. Relatively low isoconductivity variances surround the basin (Tables 2a-b). As the distance from the sampling location increases, the conductivity decreases during the whole monitoring period (Figures 4b-c). The factor loadings and rotated factor scores (varimax) are given in Tables 2c-d. The data show that more than 75% of the total variance is explained by the first three factors during the whole monitoring period. Factor 1, which includes Fe explains 34.6% of the total variance post-monsoon and 37.5% pre-monsoon, including Cu. The aerial distribution factor scores are shown in Tables 2c-d. The variables showing factor loading > 0.5 indicate moderate contamination. The zone surrounding the basin has negative or < 0.5 factor scores, demonstrating mild, no, or negative impact of stormwater on groundwater. Increasing trend score values (pre- and post-monsoon) of Pb and Zn confirm the elevated level of contamination is a result of stormwater infiltration. Whereas the decreasing trend of Cd and Fe is a result of co-precipitation of Cd with iron hydroxide [18]. Wells in the northeast, central, and southeast parts of the basin located up-gradient show high scores. Figures 3b-c show the accumulating impact of factor 1 and factor 2 pre- and post-monsoon. Wells in the southwest zone located down-gradient show negative factor scores and are apparently unaffected by factor 1 and factor 2. Wells in the southeast zone are mild or moderately affected. Factor 2 explains about 26% of the total variance, including Cd post-monsoon and Zn pre-monsoon. The aerial distribution factor score is shown in Tables 2c-d. The variable contaminated by factor 1 shows negative factor scores for factor 2 and vice versa. The uncontaminated sampling locations away from the basins also have negative factor scores. The mild contamination by Cd in the area is an impact of factor 1 on factor 2. However, it is least significant. Factor 3, which explains 17.9% of the total variance, includes Cu post-monsoon and 13.4% of the total variance includes Fe pre-monsoon (Tables 2a-b). The aerial distribution factor scores is shown in Figures 2c-d. The zone surrounding the basin has a negative factor score, which indicates that the basin is least affected by contaminants. The moderate factor loading for Cu is due to the leaching effect of salts from solid dumps due to rainfall.

Table 1: R–mode factor analysis at Hub basin.

Component Factor Loading using factor analysis

Variable	**Table: 1a**. Pre monsoon			**Table: 1b.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	-0.904	0.340	-0.012	-0.737	0.236	-0.550
Cu	-0.901	0.107	-0.317	0.885	0.231	-0.239
Pb	0.322	0.799	-0.464	-0.830	-0.275	0.302
Cd	0.368	-0.728	-0.574	-0.499	0.760	-0.235
Zn	-0.890	-0.303	0.124	0.545	0.758	0.148
Conduc	-0.940	-0.153	-0.185	0.351	0.833	-0.403
Variance	3.543	1.410	0.695	2.685	2.031	0.609
% Var	0.591	0.235	0.116	0.448	0.338	0.115

Rotated Factor Loadings (Varimax Rotation)

Variable	**Table: 1c.** Pre monsoon			**Table: 1d.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	0.850	-0.006	-0.459	-0.297	0.021	-0.902
Cu	0.957	-0.018	-0.090	0.918	-0.070	0.213
Pb	-0.090	-0.967	-0.121	-0.916	0.058	-0.119
Cd	-0.142	0.093	0.983	-0.014	0.588	-0.733
Zn	0.762	0.551	-0.122	0.696	0.627	0.122
Conduc	0.932	0.266	-0.020	0.114	-0.962	0.200
Variance	3.115	1.318	1.215	2.269	1.673	1.464
% Var	0.519	0.220	0.203	0.378	0.279	0.244

4.3 Malir Basin

The isoconductivity variance of the basin pre- and post-monsoon (Tables 3a-b) shows moderate contamination of groundwater due to the discharge of industrial effluent and stormwater infiltration, respectively. Relatively mild conductivity water surrounds the basins pre-monsoon and moderate conductivity water persists post-monsoon. Groundwater conductivity decreases as distance of the wells from the basins increases (Figures 4e-f). The factor scores are shown in Figures 3e-f. The varimax rotated factor scores are given in Table 3. Around 77% of the total variance can be explained by the first three factors. Factor 1, which includes Fe, Cu, and Cd explains 32.8% of the total variance post-monsoon and 36%, including Cd pre-monsoon. The distribution factor scores are shown in Figures 3e-f. The zone surrounding the basin records moderate loadings of Cu and Fe post-monsoon, and Cd pre-monsoon, indicating that the zone is moderately affected by the process related to factor 1. Since no variables show negatively rotated factor scores post-monsoon, this demonstrates that the zone is more or less affected by all variables related to factor 1. Factor 2, which explains 27.6% of the total variance, includes Zn and Pb post-monsoon and 26.3%, including Pb and Fe pre-monsoon (Tables 3a-b).

Table 2: R–mode factor analysis at Lyari basin.

Component Factor Loading using factor analysis

Variable	**Table: 2a.** Pre monsoon			**Table: 2b.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	-0.587	-0.636	-0.165	0.243	-0.606	-0.482
Cu	-0.576	-0.481	-0.455	0.029	-0.530	0.771
Pb	0.719	-0.132	0.363	-0.952	-0.083	-0.044
Cd	0.569	-0.671	-0.060	-0.813	0.263	0.259
Zn	-0.124	-0.471	0.811	-0.664	-0.344	-0.411
Conduc	0.543	-0.429	0.069	-0.088	-0.861	0.108
Variance	1.826	1.510	1.032	2.076	1.576	1.075
% Var	0.304	0.252	0.172	0.346	0.263	0.179

Rotated Factor Loadings (Varimax Rotation)

Variable	**Table: 2c.** Pre monsoon			**Table: 2d.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	0.105	-0.232	-0.945	-0.027	0.811	-0.027
Cu	-0.182	0.764	0.129	-0.088	-0.087	-0.927
Pb	0.678	0.208	-0.556	0.940	-0.168	-0.055
Cd	0.944	0.050	0.052	0.682	-0.574	-0.051
Zn	-0.149	-0.872	-0.053	0.783	0.323	0.066
Conduc	0.672	-0.187	-0.218	0.218	0.539	-0.650
Variance	1.867	1.479	1.272	2.018	1.416	1.293
% Var	0.311	0.247	0.212	0.336	0.236	0.216

The areal distribution factor scores are shown in Figures 3e-f. The factor scores suggest that this zone is moderately affected by the process related to factor 2 pre- and post-monsoon. The high contaminant wells have high scores of factor 2. The elevated level of rotated factor loading shows that Zn is entering groundwater through industrial effluent or nearby small landfills/physiographic depression sites responsible for the increase in Zn concentration post-monsoon. Factor 2 indicates a natural recharge process that induces Pb to groundwater, as Pb is the naturally-occurring dominant cation in the area. The variables showing negative scores indicate no or negative impact on groundwater. Factor 3, which explains only 16.5% of the total variance, includes Pb post-monsoon and 21.4% of the total variance including Zn and Pb pre-monsoon. The distribution of factor scores is shown in Figures 3e-f. The zone with a moderate factor score surrounding the basin indicates the natural recharge process that induces Pb post-monsoon, and Zn and Pb pre-monsoon. Thus the factor analysis demonstrates the zones affected by the stormwater infiltration. The results show that contaminated zones have high conductivity for Cu, moderate conductivity for Fe, Cd and Pb, and low conductivity for Zn. These results are in accordance with the results reported earlier [20].

Table 3: R–mode factor analysis of Malir basin.

Component Factor Loading using factor analysis

Variable	**Table: 3a.** Pre monsoon			**Table: 3b.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	0.300	0.568	0.632	0.655	0.391	0.194
Cu	-0.750	-0.312	0.316	0.798	0.297	-0.376
Pb	-0.258	0.852	-0.355	-0.088	0.547	0.778
Cd	0.726	-0.601	-0.024	0.556	-0.593	0.068
Zn	-0.587	-0.127	0.656	-0.040	0.869	-0.372
Conduc	0.756	0.235	0.474	0.764	-0.107	0.247
Variance	2.160	1.578	1.281	1.967	1.657	0.988
% Var	0.360	0.263	0.214	0.328	0.276	0.165

Rotated Factor Loadings (Varimax Rotation)

Variable	**Table: 3c.** Pre monsoon			**Table: 3d.** Post monsoon		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Fe	-0.079	0.187	0.878	0.737	0.033	0.275
Cu	-0.814	0.025	-0.309	0.870	0.154	-0.294
Pb	0.242	0.927	0.032	0.060	0.152	0.940
Cd	0.399	-0.853	0.059	0.321	-0.708	-0.247
Zn	-0.883	0.022	0.105	0.273	0.905	0.037
Conduc	0.277	-0.277	0.835	0.670	-0.444	0.100
Variance	1.743	1.698	1.579	1.930	1.564	1.118
% Var	0.291	0.283	0.263	0.322	0.261	0.186

5. Conclusion

Thus the factor analysis has been used successfully to delineate the zone of effluent impact and the particular ions of contamination in three basins of Karachi, Pakistan. This study has been carried out to determine the impact of stormwater on groundwater quality as a result of trace metal contamination. The factor scores indicate that the Hub basin is mainly contaminated by Cu, whereas factor scores for the Malir basin demonstrate that the groundwater is moderately contaminated by Cu, Fe, and Cd through stormwater infiltration. However, no impact of stormwater on groundwater has been noticed in the Lyari basin.

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