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Pollution loads in urban runoff and sanitary wastewater

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Abstract

While more attention has been paid in recent years to urban point source pollution control through the establishment of wastewater treatment plants in many developing countries, no considerable planning nor any serious measures have been taken to control urban non-point source pollution (urban stormwater runoff). The present study is a screening analysis to investigate the pollution loads in urban runoff compared to point source loads as a first prerequisite for planning and management of receiving water quality. To compare pollutant loads from point and non-point urban sources, the pollutant load is expressed as the weight of pollutant per hectare area per year (kg/ha·year). Unit loads were estimated in stormwater runoff, raw sanitary wastewater and secondary treatment effluents in Isfahan, Iran. Results indicate that the annual pollution load in urban runoff is lower than the annual pollution load in sanitary wastewater in areas with low precipitation but it is higher in areas with high precipitation. Two options, namely, advanced treatment (in lieu of secondary treatment) of sanitary wastewater and urban runoff quality control systems (such as detention ponds) were investigated as controlling systems for pollution discharges into receiving waters. The results revealed that for Isfahan, as a low precipitation urban area, advanced treatment is a more suitable option, but for high precipitation urban areas, urban surface runoff quality control installations were more effective for suspended solids and oxygen-demanding matter controls, and that advanced treatment is the more effective option for nutrient control.

Keywords: Pollution load; Urban runoff quality; Sanitary wastewater; Urban stormwater runoff; Event mean concentration

1. Introduction

In point source pollution, pollutants are discharged from a concentrated and recognizable source while in non-point source pollution, water flows on the surface dissolving and washing away pollutants and soil sediments along its path and finally discharging into receiving waters (Stevenson and Wyman, 1991). In urban environments, the most important point source is the discharge from the wastewater collection system; and where a treatment plant exists, this would be treated effluent from the plant.

Through time, different aspects of urban runoff have been studied by engineers. The major concern of engineers and urban planners by around 1980 was flood control and immediate transfer of the

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resulting runoff to non-urban areas. Today, designers not only consider the quantitative management and control of urban runoff, but they also place great emphasis on its quality management and control (Nix, 1994). Concern for the quality of urban runoff originated when some engineers and researchers observed that urban surface runoff accounted for most of the negative effects observed in rivers, lakes and other receiving waters downstream or within urban areas. These negative effects included acceleration in the erosion of river banks, devastation of river habitats, faster eutrophication rates in lakes, and a decline in receiving water quality. It was also observed that discharge of a large storm event may shock the receiving water body many times greater than an ordinary sanitary effluent load (Loehr, 1974; Bedient et al., 1978; WEF and ASCE, 1998; Lee and Bang, 2000).

For a water quality management plan for urban streams, the characteristics of urban runoff have been studied by a number of investigators and a considerable amount of data have been collected, the most comprehensive being the Nationwide Urban Runoff Program (NURP) in the early 1980s by the United States Environmental Protection Agency (USEPA). This program was implemented in 28 urban areas throughout the United States in which samples from 2300 rainfall events were analyzed (USEPA, 1982, 1983). The central result of the NURP studies was the development of urban runoff pollution loading factors in the form of event mean concentration (EMC).

An EMC of a pollutant in a specific catchment is obtained from the division of the total pollutant mass by the total runoff volume in that event and catchment (Eq. (1)). In a specific catchment, the weighted mean of all EMCs is the site mean concentration (SMC) determined from the division of the total pollutant mass by the total runoff volume of all measured events.

$$\mathrm{EMC}=\frac{\sum_{i=1}^{N}\overline{C}_i\overline{Q}_i\Delta t_i}{\sum_{i=1}^{N}\overline{Q}_i\Delta t_i}=\frac{\sum_{i=1}^{N}\Delta M_i}{\sum_{i=1}^{N}\Delta\forall_i} \quad (1)$$

In which N, $\overline{Q}_i$, $\overline{C}_i$, ΔM_i, and $\Delta\forall_i$ are number of samples, average runoff flowrate, average runoff pollutant concentration, runoff pollutant mass, and runoff volume in the time interval Δt_i, respectively.

The NURP EMCs are used widely in the US for a variety of stormwater management planning purposes. However, a considerable amount of urban runoff quality monitoring data has been collected in the US since the completion of NURP studies. The most comprehensive of these was a nationwide urban runoff monitoring effort, conducted by the US Geological Survey (USGS). This database includes data collected through the mid-1980s for over 1100 rainfall events at more than 97 urban sites located in 21 metropolitan areas (Driver et al., 1985; Mustard et al., 1987; Driver and Tasker, 1990). Recently, in the US, Camp Dresser and McKee (CDM) has developed an urban stormwater quality data base by combining different US data sets including the NURP data, USGS data, urban runoff data collected by cities, and others (Smullen et al., 1999).

Over the past two decades, much attention has been paid to the control of pollution by urban and industrial wastewaters through the establishment of many treatment plants in Iran. However, no steps have yet been taken to control the pollution by urban surface runoff. Before any planning is done or any practical steps are taken to control the quality of urban runoff, it is necessary to first specify the characteristics of urban runoff and to determine their pollution loads and to compare them with those of sanitary wastewater. This is one of the objectives in the present study. The unit load based on the areal contributions of pollutant (kg/ha·year) was used to determine the share of each of municipal effluent and urban runoff in the pollution of receiving waters. Once this information is obtained, it is possible to apply the best possible management method for receiving water quality control. Another objective is to evaluate the potential of various treatment options.

The city of Isfahan in Isfahan Province in Iran was the study area. The Zayandehrud River passing through the city is the water body receiving most of the runoff and sanitary effluents. The results from this study can be useful in the control and management of the Zayandehrud River water quality.

Table 1
Characteristics of the Siosepol urban catchment in Isfahan, Iran

Characteristic	Unit	Value
Population	persons	40 000
Average population density	persons/ha	110
Impervious surface area	ha	200
Total surface area	ha	360
Runoff coefficient	%	55
Average annual rainfall	mm/year	118
Length of main collector	m	6200
Average surface slope	m/m	0.02

Isfahan is an old city with a rather homogeneous makeup. There are no particular sectors of the city where commercial or other activities are concentrated. Shops and residences are generally present in all sectors. The city of Isfahan had a population of approximately 1 600 000 in 1996. There is no major industry in the city; all industries are located outside of the contributing areas to the stormwater and sanitary sewers within the urban area in this study. Isfahan is typical of a large number of cities in Iran. The annual mean precipitation for Isfahan Province is approximately 125 mm (representative of a fairly low precipitation area in Iran) (Karamouz, 1994). The mean wastewater production per capita is 175 l/d in Isfahan (IWSC, 1996).

2. Materials and methods

The city of Isfahan has 10 topographical urban catchments that each convey runoff to separate outfalls. The Siosepol catchment extending from south to center of Isfahan with characteristics listed in Table 1 was selected as the study area. The Zayandehrud River passing through the city receives runoff from the Siosepol catchment. All samples were taken at the Siosepol catchment outfall to the Zayandehrud River. The stormwater collection network for Siosepol catchment is a mixture of open and closed channels, so that main channels are closed but lateral channels are open and it is completely separated from the sanitary wastewater collection network.

Samples were taken from 10 rainfall events during December 1999 to March 2001. Rainfall characteristics of the monitored events are presented in Table 2. During an event, samples were taken at 15-min intervals during the first 2 h, at 30 min intervals during the third and fourth hours, and thereafter at 1-h intervals until stormwater flows decreased to marginal rates. At the time of all samplings, the runoff flow rates were also measured.

In this study, data were gathered on the following water quality characteristics: total solids (TS), total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), pH, conductivity, Zn, and Pb. These parameters serve as good indicators of urban runoff quality, to the effect that TS represents the total soluble and insoluble solute and pollutants, TSS represents sediment, COD represents organic loading and oxygen demand, TN and TP represent nutrients, and Pb and Zn represent heavy metals.

Table 2
Rainfall events characteristics

No.	Rainfall date	Total depth, P (mm)	Total duration, T_r (h)	Maximum intensity, I_{max} (mm/h)	Average intensity, I (mm/h)
1	12/13/1999	5.0	5.2	2.5	0.96
2	1/27/2000	7.0	6.6	3.0	1.25
3	2/13/2000	7.3	6.2	3.5	1.20
4	2/26/2000	2.5	2.6	2.5	0.96
5	11/6/2000	5.5	5.2	3.5	1.25
6	12/2/2000	4.5	5.2	2.5	0.86
7	12/10/2000	7.0	5.4	4.0	1.30
8	1/29/2001	2.0	2.8	1.5	0.71
9	2/13/2001	4.5	4.2	2.5	1.07
10	3/11/2001	4.2	5.2	1.5	0.80

All analytical procedures were based on standard methods (APHA, AWWA and WEF 1995).

The data on the characteristics of the raw sanitary wastewater and the effluent from the Southern Isfahan Treatment Plant were provided by the Isfahan Water and Sewage Co. These data were reported on a monthly basis between 1998 and 1999. The Southern Isfahan Treatment Plant is an activated sludge secondary treatment facility and its effluent discharges to the Zayandehrud River. The mean concentrations of each pollutant in the plant influent and effluent have been used in the computations of the unit loads of that pollutant.

Unit loads for wastewater, treated wastewater, and runoff were calculated based on the following equations:

$$\mathrm{WUL} = 365C \times \mathrm{PD} \times \mathrm{MWPC} \quad (2)$$

$$\mathrm{EUL} = 365C \times \mathrm{PD} \times \mathrm{MWPC} \quad (3)$$

$$\mathrm{WUL} = 10\,000\mathrm{SMC} \times P \times \mathrm{RC} \quad (4)$$

where WUL is wastewater unit load (kg/ha·year), EUL is secondary effluent unit load (kg/ha·year), RUL is runoff unit load (kg/ha·year), C is mean pollutant concentration (kg/m^3), PD is population density (persons/ha), MWPC is mean wastewater production per capita (m^3/person·d), SMC is in kg/m^3, P is rainfall depth (m), and RC is runoff coefficient.

Percentage reductions in annual pollution were based on the following equations:

$$\mathrm{APR} = 100\frac{\mathrm{EUL} - \mathrm{AUL}}{\mathrm{EUL} + \mathrm{RUL}} \quad (5)$$

Table 4
Standards for wastewater effluent quality discharged to surface water in Iran*

Characteristics	Concentration (mg/l)	
	Average	Instantaneous
BOD_5	30	50
COD	60	100
TSS	40	60
TN	16	–
TP	6	–
Pb	1	–
Zn	4	–
pH	6.5–8.5	–

*DOE (2001).

$$\mathrm{DPR} = 100\frac{\mathrm{PE} \times \mathrm{RUL}}{\mathrm{EUL} + \mathrm{RUL}} \quad (6)$$

where APR is percent reduction in annual pollution load due to employing advanced treatment in lieu of secondary treatment (%), DPR is percent reduction in annual pollution load because of establishing runoff detention installation (%), AUL advanced treatment unit load (kg/ha·year), and PE is efficiency of the runoff detention installation.

3. Results and discussion

A statistical summary of urban stormwater runoff quality data for the Siosepol catchment is given in Table 3. Currently, in Iran, there are not any specific regulations for urban runoff quality discharged to local surface water. Table 4 lists wastewater effluent requirements for Iran, these standards are near those in the US and elsewhere in the world. In Fig. 1, the water quality charac-

Table 3
Statistical summary of EMCs of water quality characteristics for the Siosepol catchment from 1999 to 2001

	TS (mg/l)	TSS (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Pb (mg/l)	Zn (mg/l)	pH (−)	EC (μS/cm)
Maximum EMC	3177	467	2542	22.38	0.790	0.558	2.386	7.6	2015
Minimum EMC	230	43	139	1.22	0.064	0.018	0.015	6.9	202
S.D.	853	133	713	6.23	0.209	0.221	0.737	0.2	579
Arithmetic mean	888	161	561	6.65	0.274	0.278	0.342	7.3	577
Flow weighted mean (SMC)	963	149	649	6.75	0.274	0.314	0.453	7.3	507

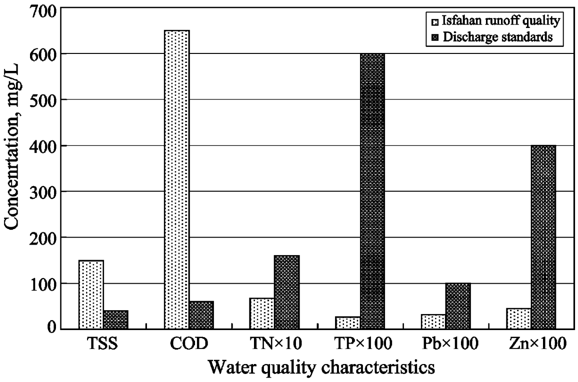

Fig. 1. Comparison of water quality characteristics between Isfahan stormwater runoff and the standard level of permit discharge.

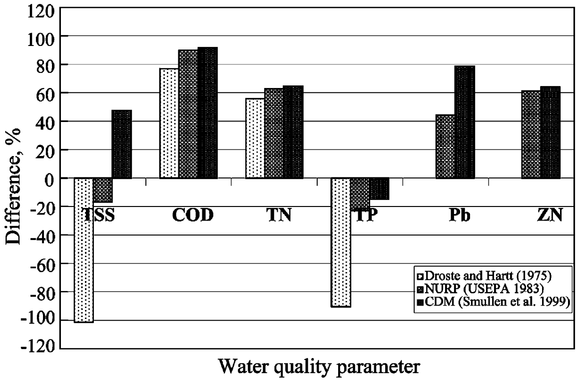

Fig. 2. Comparison of percentage differences between EMCs of Isfahan stormwater runoff and three data bases.

teristics in Isfahan stormwater runoff are compared with those in the standard level of permit discharge. Urban runoff quality in terms of suspended solids and organic matter is highly polluted and it is above the specific level of permit discharge defined by environmental regulations. The concentration of Zn in surface runoff is far less than the permitted limit in drinking water, i.e. 5 mg/l (De Zuane, 1990; ME and OMP, 1992; USEPA, 2002); the standard value for treatment effluents, 2 mg/l (USEPA, 1992; DOE, 2001); and the recommended water quality criteria for freshwater, 0.120 mg/l, and for saltwater, 0.090 mg/l (USEPA, 1999).

The EMCs of Isfahan stormwater runoff are compared to those of NURP (USEPA, 1983) and CDM (Smullen et al., 1999) data bases of the US and Droste and Hartt (1975) of Canada in Table 5. Fig. 2 illustrates the percentage differences between EMCs of Isfahan stormwater runoff and these data sources. The differences between the Isfahan means and those estimated from the other data sets range from a 101% lower estimate for TSS to a 92% higher estimate for COD. The explanation will focus on the differences between Isfahan means and the CDM means as a more recent and comprehensive data base for North American cities. All Isfahan means (except TP) are higher than CDM means and it shows that Isfahan urban runoff is more polluted than runoff for North American cities. This is because of higher population density, more littering, and using manual sweeping activities in Isfahan. The lower TP mean in Isfahan runoff in comparison to the CDM mean (15%) is probably because of less

Table 5
Comparison of Isfahan and North America EMC estimates

Quality parameter	Unit	Isfahan runoff	Droste and Hartt (1975)	NURP (USEPA 1983)	CDM (Smullen et al., 1999)
TS	mg/l	963	–	–	–
TSS	mg/l	149	300	174	78.4
COD	mg/l	649	150	66.1	52.8
TN	mg/l	6.75	2.98	2.51	2.39
TP	mg/l	0.274	0.522	0.337	0.315
Pb	mg/l	0.314	–	0.175	0.067
ZN	mg/l	0.453	–	0.176	0.162
pH	–	7.3	7.4	–	–
EC	μS/cm	507	300	–	–

Table 6
Statistical data for influent and effluent quality characteristics for the southern Isfahan wastewater treatment plant from 1998 to 1999

	Raw wastewater (influent)			Treated wastewater (effluent)		
	TSS	COD	TP	TSS	COD	TP
Mean (mg/l)	215	443	38.7	37	89	15.9
Maximum (mg/l)	302	612	92.0	59	130	36.0
Minimum (mg/l)	133	237	13.4	26	65	3.5
S.D. (mg/l)	51	100	20.7	10	19	9.0

green land and as a result, less usage of fertilizer in Isfahan.

Table 6 presents a statistical summary of the characteristics of the raw sanitary wastewater and the effluent from the Southern Isfahan Treatment Plant obtained through statistical analysis of the data provided by Isfahan Water and Sewage Co. The mean concentrations for the selected water quality characteristics (TSS, COD, and TP) in runoff, raw sanitary wastewaters, and secondary effluents from Isfahan Treatment Plant are compared in Fig. 3. It is readily observed that urban runoff is seriously polluted; the mean concentrations of oxygen demanding material in these flows are far greater than the concentrations of the same contaminants in raw sanitary wastewater. The concentration of TSS in urban runoff is lower than that in raw sanitary wastewater but higher than that in secondary effluent. The concentration of phosphorus in urban runoff is lower than that in raw sanitary wastewater and secondary effluents.

Another discrepancy observed in the qualities of urban runoff and sanitary wastewater is the vast range of variation in the quality of urban surface runoff. The range of variation in the quality of surface runoff is far greater than the range of variation in the quality of raw or treated sanitary wastewater (Tables 3 and 6). This makes urban surface runoff quality control more difficult.

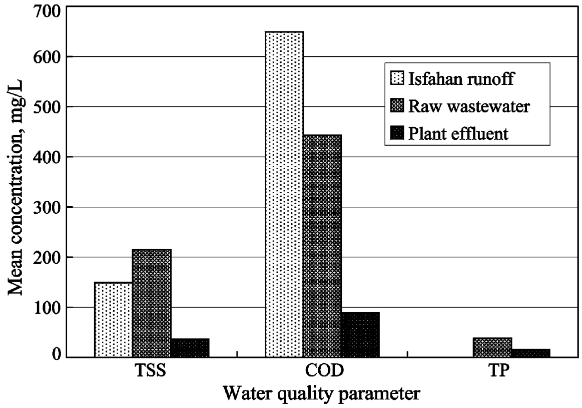

Fig. 3. Comparison between mean concentrations for contaminants in Isfahan urban runoff, raw sanitary wastewater and secondary treatment effluent.

No proper receiving water quality management method can be defined solely on the basis of measured pollutant concentrations in urban runoff and sanitary wastewaters because sanitary wastewaters are continuously discharged into receiving waters; the discharge of surface runoff is discontinuous and transient. It follows that the unit load of contaminants may be a better basis for determining the management method of the receiving water quality. Based on the data gathered for the flow of runoff, sanitary wastewater, and plant effluents, the unit loads of TSS, COD, and TP were calculated in kg/ha·year in Table 7.

Table 7
Unit loads for contaminants in surface runoff, raw wastewater, and secondary treatment effluents in kg/ha·year

Parameter	Raw wastewater (WUL)	Plant effluent (EUL)	Urban stormwater runoff (RUL)		
			Isfahan (P=118 mm/year)	Mild precipitation urban area (P= 500 mm/year)	High precipitation urban area (P= 1000 mm/year)
TSS	1511	260	97	410	820
COD	3113	625	421	1785	3570
TP	272	112	0.2	1	2

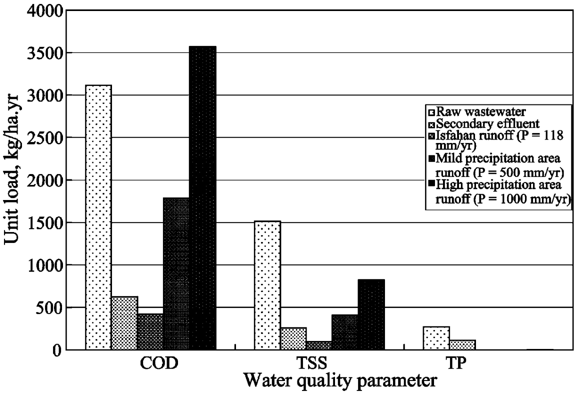

Fig. 4. Comparison between unit loads in raw sanitary wastewater, secondary treatment effluent, Isfahan urban runoff, mild precipitation area, and high precipitation area.

The unit loads for contaminants in Isfahan surface runoff are compared between raw wastewater and treated effluents in Fig. 4. In Isfahan, the annual pollution load in urban runoff is lower than the annual pollution load in raw sanitary wastewater and also lower than that in secondary treated effluents (Fig. 4). This finding is site specific. It is interesting to examine other urban watersheds with higher annual precipitation. There are not enough data on urban runoff quality of other cities in Iran. Also, any attempt to find a meaningful relationship between the EMC or unit load and the total depth event rainfall or total event runoff volume for Isfahan monitored events failed. Bedient et al. (1978) found linear relationships between unit loads and total depth of events for several Houston area watersheds. These relationships varied in different areas even in Houston, so they are not applicable in other places. Therefore, a rational hypothetical condition as an illustration example was used as follows:

In the large cities of Iran (with population more than 1 000 000 except Tehran), because of the similarities in population density, in mean wastewater production per capita and in wastewater characteristics, the wastewater unit loads are roughly similar. It is assumed that these cities have SMCs of contaminants the same as Isfahan regardless of their annual precipitation. This is probably not a correct assumption and lacking a universal relationship in this regard, a specific study should be conducted for each urban area. However, in the cities of Iran there are regular daily street sweeping activities for all dry weather conditions and in the wet weather conditions the urban surfaces are cleansed by runoff. Therefore, SMCs will be less dependent on geographical conditions and the length of time from the last event.

Annual precipitations of 500 and 1000 mm/year were used as representatives of mild- and high precipitation urban areas, respectively. The unit loads for urban runoff in these urban areas are compared with unit loads of wastewater and secondary effluents in Fig. 4. It can be observed that all annual contaminant loads in urban runoff are lower than the annual contaminant loads in raw sanitary wastewater but greater than in treated effluents (except for TP); therefore, controlling the quality of urban runoff in these areas is more important than controlling the quality of effluent from a secondary wastewater treatment plant. Fig. 4 reveals that the annual loads of oxygen demanding matter in urban runoff in high precipitation areas are potentially greater than the same loads in raw sanitary wastewater. Therefore, in these areas more consideration must be given to the control of urban runoff quality. This is because the short-lived discharges of urban runoff into receiving waters cause serious environmental shocks to them. Lakes may not experience as severe of a shock as streams because longer residence times in lakes contribute to equalization of cumulative effects of sanitary discharge and precipitation events; however, urban runoff dominates loads to the lakes.

Where the quality of receiving water is critical and pollution discharge in water bodies is serious, it is necessary to evaluate the effect of advanced treatment processes (in lieu of secondary treatment) against the effect of urban runoff quality control installations (such as detention ponds). Typically, effluents from advanced treatment have TSS of 10 mg/l, COD of 10 mg/l, and TP of 10 mg/l. It is expected that well designed and operated detention installations for runoff are capable of TSS, COD, and TP reductions of 90%, 60% and 50%, respectively, (USEPA, 1983). Under these conditions, the percentage reductions in all annual urban pollutants discharged form both secondary treatment effluent and urban stormwater runoff into receiving waters were calculated according to Eqs. (5) and (6) in Table 8.

The percentage reductions in annual load of urban pollution discharges due to selecting advanced treatment in lieu of secondary treatment are compared with percentage reductions due to establishing runoff detention installations in Fig. 5. In low-precipitation areas such as Isfahan, on an annual load basis, pollution removal is better achieved by an advanced treatment processes compared with surface runoff detention installations (Fig. 5). In mid- and high-precipitation areas, TSS and BOD removals can be better achieved through detention systems and TP control is accomplished by advanced treatment. It follows that the percentage of annual pollutant discharge reductions by advanced treatment or surface runoff detention installations can be estimated on the basis of the type of contaminant controlled and the amount of annual precipitation in the area. The result would be the selection of a more appropriate and more effective method for the reduction of annual pollutant discharges into receiving waters.

It must be emphasized that the above conclusions and analyses are based on the assumption that SMC is not affected by rainfall volume. Furthermore, areal sanitary discharge and urban runoff loading rates will be affected by population densities and local practice. However, this study

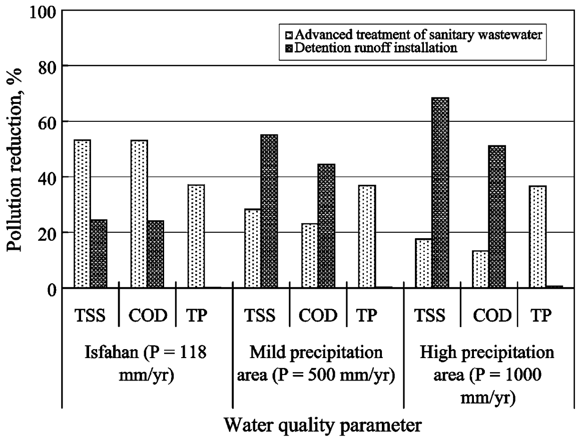

Fig. 5. Comparison between the percentage reduction in annual load of urban pollution discharges due to selecting advanced treatment in lieu of secondary treatment and those due to establishing runoff detention installations.

points to the need to conduct screening studies of this nature to prioritize treatment schemes to meet receiving water quality objectives.

4. Conclusions

The results from this study can be summarized as follows:

1. Urban stormwater runoffs are highly polluted; in Isfahan the mean concentrations of oxygen demanding matter in them are much higher

Table 8
Percentage reduction in annual load of urban pollution discharges due to selecting advanced treatment in lieu of secondary treatment and establishing runoff detention installations

Urban area	Contaminant	Advanced treatment in place of secondary treatment	Runoff detention installations
Isfahan	TSS	53.2	24.4
($P = 125$ mm/year)	BOD	53.0	24.1
	TP	37.0	0.1
Mild precipitation	TSS	28.3	55.1
($P = 500$ mm/year)	BOD	23.0	44.4
	TP	36.9	0.3
High precipitation	TSS	17.6	68.3
($P = 1000$ mm/year)	BOD	13.2	51.1
	TP	36.6	0.7

than in raw sanitary wastewater. The concentration of TSS in urban runoff is lower than in raw sanitary wastewater but higher than in secondary effluent. The concentration of phosphorus in urban runoff is far lower than that in sanitary wastewater and secondary treatment effluents. Lead and zinc concentrations in urban runoff, which are higher than the concentrations of other heavy metals due to motor vehicle traffic, are far lower than the standard limits in treatment effluents. US NURP typical values are not applicable.

2. Variations in urban runoff quality are greater than variations in raw or treated sanitary wastewaters.
3. General indications from this study for cities in Iran with conditions similar to Isfahan are as follows. In low precipitation areas (less than 200 mm/year), the annual pollutant load of urban runoff is usually lower than the pollutant load in raw sanitary wastewater and secondary treatment effluents. The annual load of suspended solids and oxygen demanding matter in urban runoff in mild precipitation urban area (up to 500 mm/year) is usually lower than the pollutant load in raw sanitary wastewater but higher than the annual load in secondary effluents. In high precipitation urban areas (more than 500 mm/year) the annual load of suspended solids and oxygen demanding substances in runoff is increasing to a comparable level of the annual load of these substances in raw sanitary wastewater. The annual load of nutrients in raw sanitary wastewater and secondary effluent is commonly higher than the annual load of nutrients in urban runoff.
4. In areas where the control over urban pollution discharges into receiving waters is vital, the percentage of annual contaminant discharge load reductions through advanced treatment (in lieu of secondary treatment) must be evaluated against the percentage reductions in the annual contaminant discharge load by runoff quality control installations. The effectiveness of each option depends on the pollutant controlled and the precipitation pattern in the area. For Isfahan, advanced treatment is a more suitable option, but for mild- or high precipitation urban areas, generally, to control suspended solids and oxygen-demanding matter, stormwater runoff quality control installations (such as detention ponds) are more effective than advanced treatment, while in the case of nutrients, advanced treatment is a more effective option.

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