Technical Report III - 2

Environmental Impact Issues Related to Recharge Enhancement and Irrigation in the Sana'a Basin

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1. Introduction

Widespread wastewater disposal through cesspits to the underground has deteriorated to a substantial degree the quality of groundwater under some parts of the city of Sana'a. This pattern of groundwater contamination correlates well with population density, as groundwater under the central zone of the city tends to be more contaminated than that under the less densely populated southern and northern zones. Much of the contaminated groundwater is being pumped up again to the city for further use, while the remaining part is expected to follow the general groundwater flow towards the north. Nevertheless, the slow horizontal movement of the deeper groundwater and heavy pumping suggest a slow horizontal spread of pollution.

In order to be able to conclude that the direct disposal of domestic wastewater into the sub-soil layers has resulted in groundwater contamination, the background water quality, and the representativeness of the sampling program need to be known. Although the different zones of the city were not covered equally in the number of wells sampled by Al-Hamdi (Al-Hamdi, 2000), they were selected to reflect the different population densities within the city. Even though the northern part of the city was under-represented, water quality data of three NWSA production wells located to the north of the city are used to compensate this deficiency. Given that the groundwater system in Sana'a consists of three aquifer layers in addition to a complex local geology, it is quite difficult to determine with certainty the aquifer from which a well taps. Although the results cannot be attributed to a particular depth, the selected wells are assumed to generally represent the deeper, more productive Tawilah sandstone aquifer.

It was corroborated by different researchers that domestic sewage has been infiltrated to the groundwater via cesspits all over the Sana'a city area. As a result of groundwater analysis and modeling of hand dug and drilled wells, the hydrochemical maps showed that EC values ranged 500-3500 (SAWAS-13, 1996). Highest values are found in the old part of Sana'a and near the sewage ponds. Although NO_3^- could originate in some aquifers from magmatic NH_3 gas or from the fertilizers used in the agriculture area, it was proven that high Cl^-, NO_3^-, SO_4^{2-}, HCO_3^- and Fecal Coliform were a clear indication of infiltration of domestic sewage (SAWAS-13, 1996).

Al-Hamdi suspected that the wastewater discharged to the underground is gradually diluted with groundwater, and partially pumped back up for use within the city. Although in need for further investigation, the slow groundwater flow in Sana'a suggests that the horizontal spread of pollution due to groundwater flow will take a time several orders of magnitude longer than vertical transport due to the high abstraction rate within the city.

The main objective of this report is to give an overview of the potential pollution aspects related to wastewater re-use in the Sana'a urban and propose monitoring program for the aquifer under risk. For a more detailed evaluation of the quantitative aspects of re-use the writer is referred to Volume IIof this report.

2. *Environmental Aspects of Wastewater Treatment*

2.1 Wastewater treatment technology

Wastewater treatment is an inevitable step to prevent public health risks by preventing the odor and to stop the overflow of cesspits on streets as the case in Sana'a (own observations). It will also stop the soil and groundwater pollution. It should also stop the non-biodegradable pollutants from industries. Nevertheless, the scarcity of water resources may compel the use of wastewater to reduce the exploitation of groundwater for agricultural uses. This requires the adoption of specific treatment strategy.

Treatment objectives and degree of treatment should be chosen based on the discharge criteria. Wastewater origin and constituents are very important factors affecting choosing and design of the type treatment system adopted. Economical and climatical situation skilled labor and supervision needed should also be considered when choosing the treatment system. Mechanized systems need an area of 0.16-0.35 m^2/ person compared to 1-2.8 m^2/person for the land extensive systems (Table 1).

Table 1. Main difference between mechanized and land–extensive wastewater treatment systems (Al-Nozaily, 2001).

Issue	***Mechanized sys.***	***Land-extensive sys.***
Biomass	Aerobic and anaerobic	heterotrophs, algae and aquatic
Characteristics	high active biomass, high rate	ecological symbiosis, low rate
Area required	small (0.16-0.35m2/person)	large (1-2.8m2/cap)
Mechanization cost	high	low
BOD removal	good (90-98%)	fair (80-95%)
FC, helminth and viruses	poor (1-2 log)	good (2-6 log)
Odor at high sulfate	odor in P.S.T	susceptible
Excess sludge production	much and unstable (poor)	Less and stable (good)
O&M need	high	low
Energy need	very high	low
Labor needs	skilled	semi-skilled (if routine operation)

Land extensive (low rate processes) treatment systems available are Waste Stabilization ponds (WSP), Aerated Lagoons (AL) or Duckweed-based Sewage lagoons (DSLs). Mechanized systems (high rate processes) treatment systems are Activated sludge (AS), Trickling Filters (TF) or Rotating Biological Contactors (RBC). For Sana'a, the Activated sludge system was adopted. AS systems can be classified by F/M (food to microorganisms) ratio. At very low F/M ratio the ammonia in the wastewater is expected to nitrify completely and the sludge is expected to become stable. However, the needed aeration time (t_{AT}) will be more than 24 hrs (Table 2).

Table 2. Classification of activated sludge treatment plants by F/M ratio at moderate climate conditions (Veenstra and Van Duijl, 1995)

Category	***F/M (kgBOD/kg MLSS.d)***	***Nitrification***	t_{AT}	***MLSS (mg/l)***	***Biomass***
High	>1	non	1 h	2000	not stable
Medium	0.2- 1	partly	≥2 h	3000	not stable
Low	<0.2	complete	≥3 h	3500	not stable
Very low	<0.05	complete	≥24 h	4000	stabilized

Moreover, the F/M ratio is the key parameter to chose the required treatment objective as shown in Table 3.

Table 3. Treatment objectives vs. required F/M ratio at sewage temp. of 10℃ (Veenstra and Van Duijl, 1995)

Treatment objective	***Required F/M (kgBOD/kgMLSS.d)***
High BOD removal	<0.3
Biological P removal	<0.25
Nitrification	<0.15
Denitrification	<0.12
Sludge stabilization	<0.05

2.2 Evaluation of the new (existing) Sana'a WWTP

The system is AS with Extended Aeration; the area of the land used for the treatment system is 30 ha. With served population of 600,000cap, the specific area need is $0.5m^2$/cap. The cost of construction is US$34Million, the specific cost is US$ 55-60/cap. Design parameters and actual (measured) parameters are listed in Table 4.

Table 4. Comparison of design and actual values in the new (Existing) Sana'a wastewater treatment (Dar Al-Handasah, 2000-II; NWSA, personal comm.).

Parameter	***Design value***	***Actual value***	***Remarks***
Average capacity	$50,000m^3/d$	$20,000m^3/d$	under capacity
BOD_{in}	500mg/l	1100-1200mg/l	higher values
BOD_{out}	30mg/l	55mg/l	Ok
TSS_{in}	750mg/l	900-1000mg/l	higher values
TSS_{out}	30mg/l	30mg/l	Ok
$NH_4^+{}_{in}$	100mg/l	200mg/l	higher
$NH_4^+{}_{out}$	5mg/l	60mgN/l	higher

Comparing the design parameters with the actual measured parameters (Table 4), the following can be concluded:

- Sana'a treatment plant is still under capacity in terms of flow.
- Removal efficiency (%) are acceptable (BOD as 94-97%, TSS as 96-97% and NH_4^+ as 70% with effluent NO_3^- of 30-40mgN/l).

However, wastewater characteristics as BOD, SS and NH_4^+ are two times as much as the design values.
Applying the average BOD of 1060mg/l, this will result in a BOD load of (20,000*1060/1000=) 21200 kgBOD/day.
Moreover, the reported operation parameters as follows:

- SVI= 130 ml/g (acceptable; 75-150ml/g for good settling).
- S_r (sludge recirculated)= 17g/l (higher than the design values of 8-13).
- MLSS= 10952 mg/L (higher than the acceptable value of 4000 mg/l; At >4000 mg/l, hindered settling will exist.

Given that volume of aeration tank is 95256m^3, the F/M ratio will be (21200/(95256*10.952)=0.020kgBOD/kgMLSS.d. Comparing with the F/M ratio in tables 2 and 3, the sludge is expected to be stable with nitrification and denitrification should be complete. However, this is not the case: from the actual meagrement NH_4^+ of 60mg/l at the effluent is still high; NO_3^- =30-40mg/l is still high (NWSA, Personal Communications). The following can be concluded:

- Sana'a treatment plant need to be investigated to study the reason behind the incomplete are Nitrification and denitrification
- The sludge recirculated (S_r) should be decreased to the design value
- MLSS (biomass concentration in the aeration tank should be less than or equal to 4000mg/l in order to avoid hindered settling. At this moment SVI value will be depend on MLSS value in the aeration tank.

The actual operational line of the WWTP is shown in figure 1. Looking at this figure, the sludge is recirculated from the final settling while the excess sludge is removed from the aeration tank and not from the settling tank as designed and pumped to the thickeners. After that the sludge is pumped to the drying beds. Natural drying systems require long hydraulic retention times, no energy input and do not rely on high technical equipment. Therefore, when land is available at low cost and the climate is suitable for evaporation, as the case in Sana'a, drying beds can be applied and the sludge is expected to by dried up to 50%.

However, this is not the case. For Sana'a treatment plant, sludge is not dried enough as designed. The DS after the design drying retention time of 10 days is still 20-25% instead of being 50% according to the design. Even after 16 days retention time, the DS is still only 35%.

Due this high moisture content, the sludge handling has become a burden and it is piling in the site. Farmers are hesitating to apply it due to its high water content and due to the attachment of the sand from the drying beds. Therefore, the following is recommended:

- to remove the excess sludge from the final sedimentation tank instead of from aeration tank.

- to investigate the nature of the sludge and the reason behind the inadequate dryness in the drying beds according to the design.
- It is recommended not to use mechanical equipment and keep the natural system.

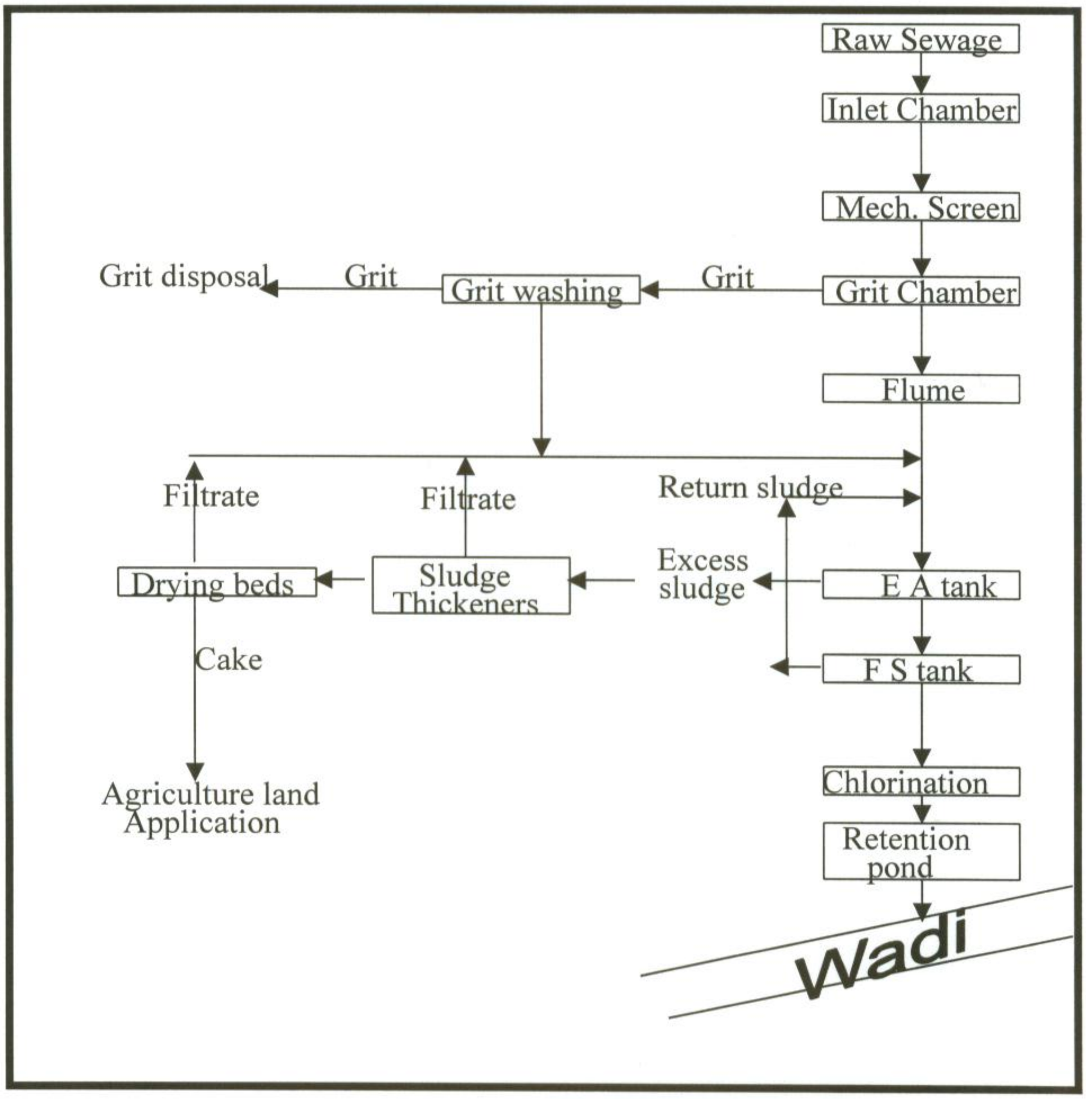

Fig. 1. Flow diagram for The new Sana'a Treatment plant(SAWAS)

2.3 Quality standards for reuse in irrigation

In order to be able to use the wastewater for irrigation, industrial wastewater should only be allowed to discharge their effluents to the sewerage system when the permissible limits are met in Table 5.

Table 5. Permissible limits for industrial effluent (Al-Guneed and Bin Ali Gaber, 1998).

Parameter	***Conc mg/l***	***Parameter***	***Conc mg/l***	***Parameter***	***Conc mg/l***
COD	200	S	1	Cu	5
BOD	50	H_2S	1	Pb	0.6
pH	5.5-9.5	Fe	50	Hg	0.01
Temp	45	Cl^-	600	Ni	5
TSS	500	F^-	8	Se	1
TDS	2000	As	0.1	Ag	1
Oil&greese	100	Sn	10	Mn	10
Phenol	2	Ba	3	Be	5
Sulfate	1000	Br	5	Zn	10
P	50	Cd	1		
Cn	5	Cr	5		

The following guidelines of the wastewater treatment effluent should be adopted as shown in Table 6 (Adapted from FAO, 1991).

Table 6. Adapted FAO guidelines for treated effluent reuse in agriculture (Bin Ali Gaber, 1997).

Standard	***Parameter***	***Unit***	***limits***
Salinity	EC_w TDS	Mmhos/cm mg/l	0.7-3 450-2000
Infiltration	SAR EC	SAR Mmhos/cm	0-40 0.2-5
Na	Surface irrigation Sprinkler irrigation	SAR meq/l	3-9 <3.0
Cl^-	Surface irrigation Sprinkler irrigation	meq/l meq/l	4-10 <3.0
Boron	B	mg/l	0.7-3.0
Nitrogen	N	mgN/l	5-30
Bicarbonate	HCO_3^-	meq/l	1.5-8.5
Hydrogen ion	pH	-	6.5-8.4

EC_w: Electrical conductivity in deci Siemens per meter at 25°C

SAR: Sodium adsorption ratio.

Table 7. Guide lines of heavy metal conc. in wastewater effluent used for irrigation (Al-Guneed and Bin Ali Gaber, 1998).

Parameter	***Conc mg/l***	***Parameter***	***Conc mg/l***
Al	5.00	Li	2.50
Arsenic	0.10	Mn	0.20
Beryllium	0.10	Mo	0.01
Cadmium	0.01	Ni	0.20
Cobalt	0.05	Pb	5.00
Cr	0.10	Se	0.02
Cu	0.20	Vanadium	0.10
F	1.00	Zinc	2.00
Fe	5.00		

2.4 Projection of wastewater generation in Sana'a

Table 8. Projection of wastewater generation in Sana'a (Dar Al-Handasah-1, 2000)

Year	***Population***		***Water consumption***	***Wastewater production***		***Treatment capacity***
	total	served	l/c.d	l/c.d	m^3/d	m^3/d
2000	1,282,968	353,135	66	52.8	13,425	50,000
2005	1,641,096	1,106,715	76	60.8	67,290	75,000
2010	2,006,040	1,384,440	86	68.8	95,250	100,000
2015	2,399,660	1,769,690	100	80.0	141,575	150,000
2020	2,822,431	2,041,940	114	91.2	186,225	175,000

It has been proposed that construction of 25,000 m^3/d modules should be available at the proper time. One module at the site of the new treatment plant. The last 4 modules will be constructed at the old cite in Al-Rawdah. The southern area of Sana'a city to be provided with on-site disposal facilities (Dar Al-Handasah-I, 2000). Moreover, as shown in the following Maps (Dar Al-Handasah, 2000-III and Al-Muta'a, Personal Communication), the sanitary sewers are only executed in part of the city (Fig. 2). Sewage flooding is still taking place in some places (Fig. 3) while the New sewerage systems will be constructed and connected to the treatment plant at different stages (Fig. 4). For the coming period of time until the sewers are executed, the cesspits will drain the wastewater to the soil and will continue polluting the groundwater. Therefore, the suggested on-cite treatment for the southern area of Sana'a should not be cesspits. It should be used septic tanks and the wastewater should be treated in a ponds and used for irrigation. The same system should also be applied to the southern part of Sana'a where the on-site system is proposed. Moreover, the existing cesspits at the areas served with sewers should be pumped and evacuated to stop the drainage of the contents to the groundwater aquifer.

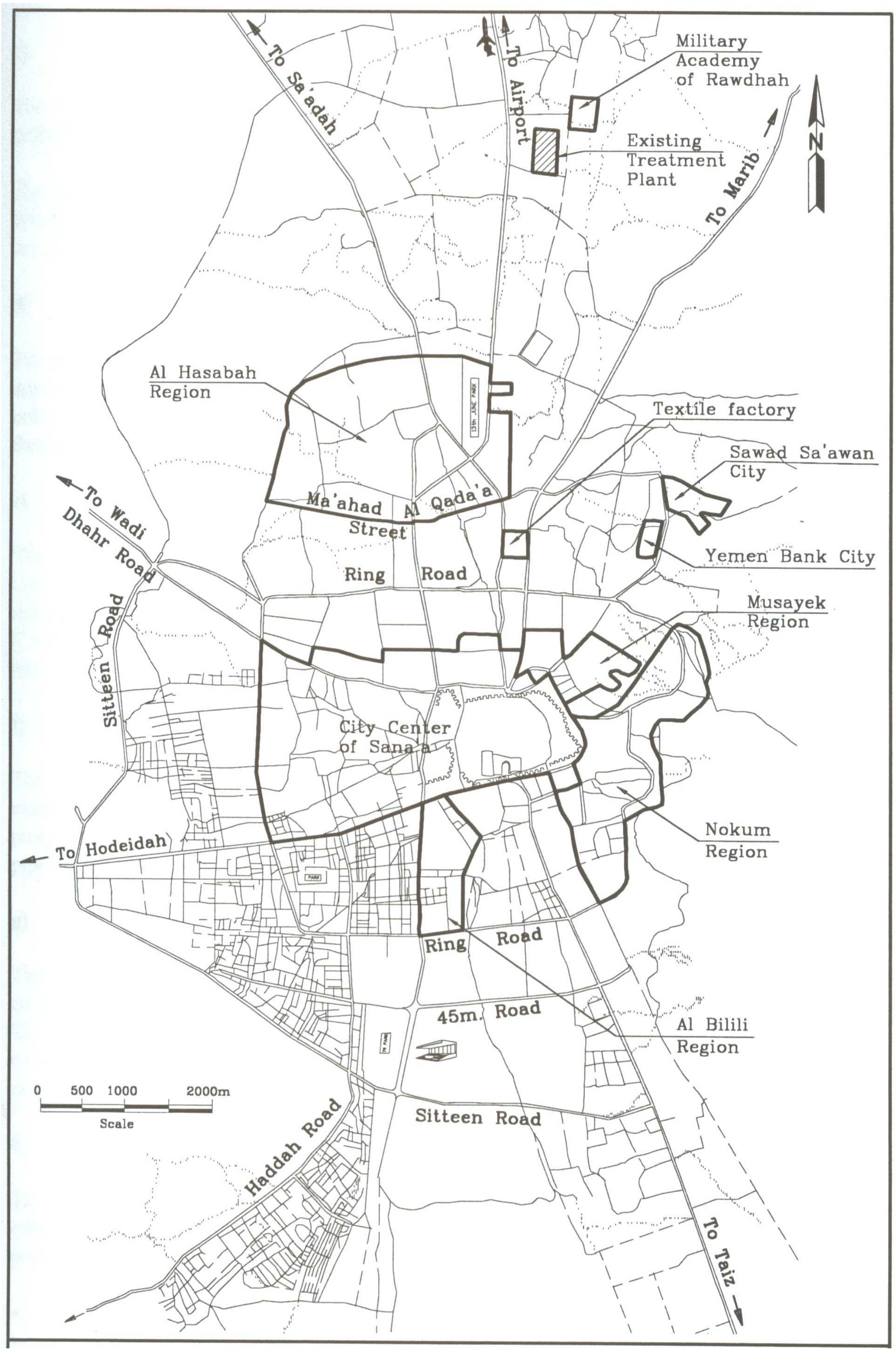

Fig 2 : The Existing sewerage System (Dar Al-Handasa, zone III)

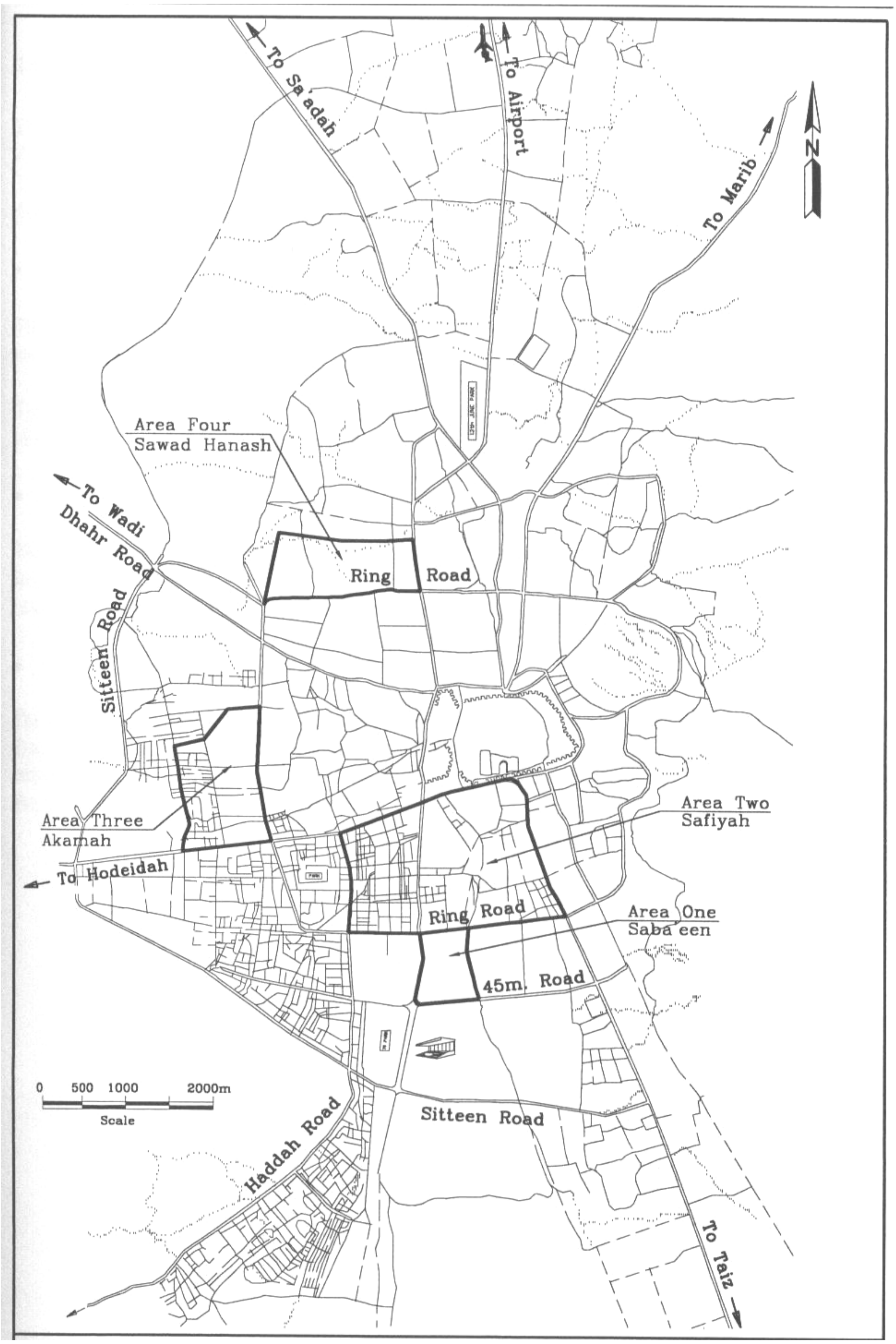

Fig 3 :Locations of areas suffaring from sewage flooding problems (Dar Al-Handasa, zone III)

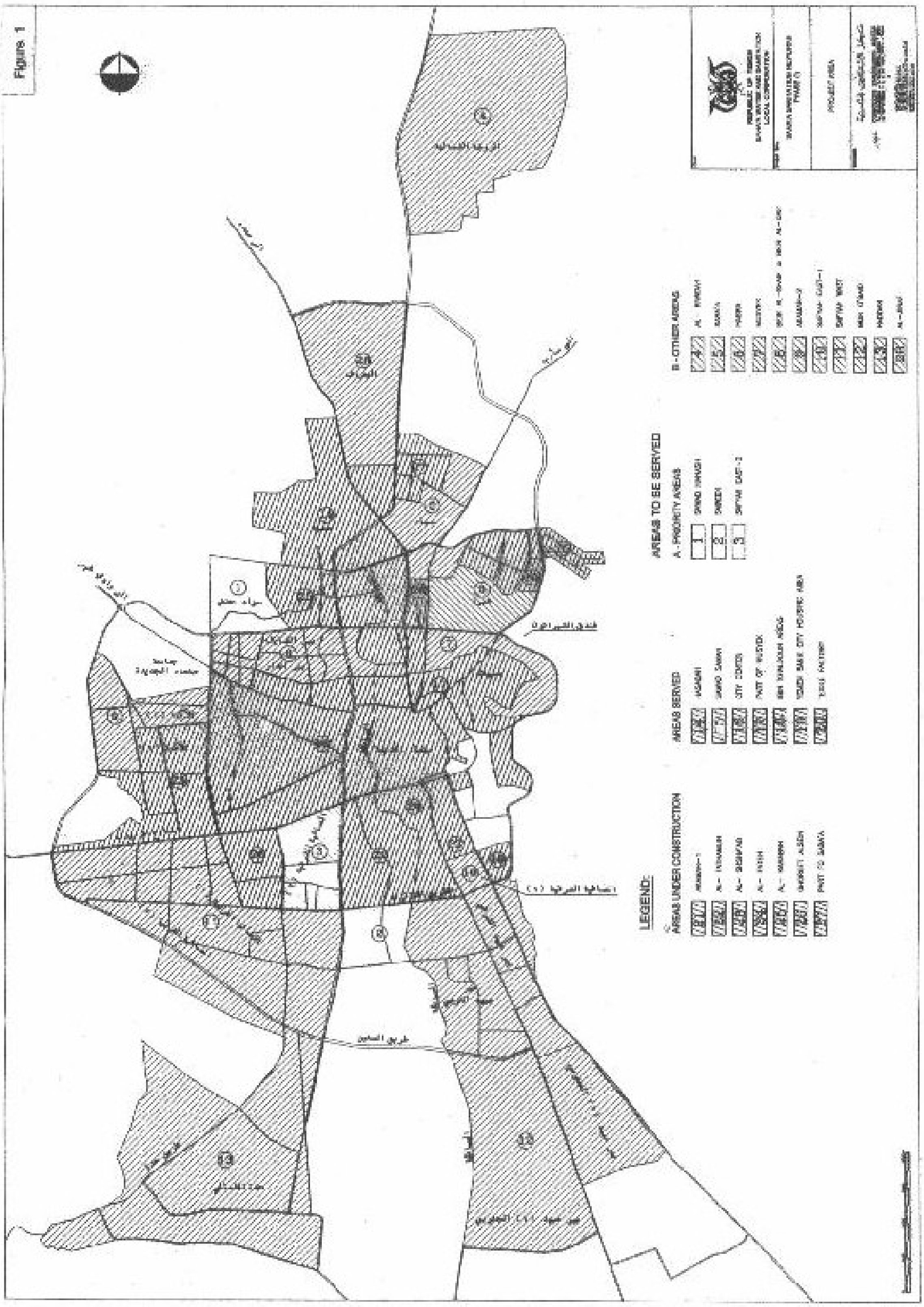

Fig. 4 : Areas Constructed and underconstruction and others which will not be constructed. (Dar Al-Handasa, zone III)

3. *Environmental Impacts Within the Context of Reuse*

Discussion of the different options for wastewater re-use in the Basin and evaluation of different scenarios is given in Volume II of the report (see section 4.6). In this section, we deal with the environmental impact aspects of wastewater re-use only. The direct effect of the reuse alternatives on the quality and integrity of groundwater is used as the main indicator of environmental impact. Results of different scenarios are given in table.9. A score of 0 to -3 is used to evaluate the extent of groundwater contamination; 0 indicates no damage and -3 reflects maximum contamination and irreversible deterioration. For the reuse alternatives that involve irrigation of fodder, cereals, cash crops, or municipal parks (scenarios 1, 2, 5), a score of -1 is used to reflect the effect of return flows on the quality of the receiving groundwater. For scenario 3, a maximum score of -3 reflects the expected local long-term change in the quality of groundwater. The extra wastewater treatment prior to the recharge and recovery for potable use (scenario 4) justifies the low risk score of -1. Since no direct discharge is associated with scenario 6, a score of 0 is appropriate.

Table 9: Multi-criteria analysis of wastewater reuse scenarios in Sana'a. (Al-Hamdi, 2000)

Criterion / Scenario	(1)	(2)	(3)	(4)[a]	(5)[b]	Arithmetic sum[b]
(1)	-1	0	0	-1	-2 (-6)	-4 (-8)
(2)[c]	-2	-2	-2	-1	0 (0)	-7 (-7)
(3)[c]	0	-2	0	-3	0 (0)	-5 (-5)
(4)	-1	-3	-3	-1	0 (0)	-8 (-8)
(5)	-1/-2	-2	-1	-1	-2 (-6)	-7/-8 (-11/-12)
(6)	-2	-3	-2	0	0 (0)	-7 (-7)
	0 = No risk -3= Max. risk	0=No extra cost -3=Max. cost	0=Max. accep-tance -3=Min. accep-tance	0=No threat -3=Max. threat	0=Max. contribu-tion -3=No contribu-tion	

a Reflects mainly groundwater contamination.
b Values between brackets have been multiplied by a correction factor of 3.
c Using wastewater to replace groundwater.

Table 9 identifies two distinctive categories of feasible reuse alternatives: those with a summation of less than –5, and those with a summation of greater than or equal to -5. The two scenarios 1 and 3 have the highest overall score and are the most appealing. On the other hand, scenarios 5 and 4 have the lowest potential. Even though wastewater reuse for fodder and cereal crops appeared earlier to be an obvious option, it shifts to the less-appealing category after corrected for water scarcity. Although this alternative brings an extra income for some local farmers, it does not contribute towards the conservation of water resources. It is clear from Table 9 that the only truly attractive alternative for wastewater reuse in Sana'a is groundwater recharge and recovery for irrigation of existing groundwater-irrigated cash crop fields.

4. Environmental Monitoring

4.1 Methodology

In this proposal the pollution is considered to take place due to the wastewater infiltrated into the groundwater aquifer through two sources:

1. Non-point source: This is due to the several cesspits located in the urban area of Sana'a
2. Point source of wastewater treatment plant situated Beside Sana'a Airport

The pollution expected through the cesspits will happen directly while that through the wastewater treatment plant will take place through applying the effluent wastewater in the agriculture, which will be infiltrated through the permeable soil to the aquifer.

To assess the impact of these two sources, one has to consider different measures to undertake monitoring and follow-up during the project implementation.

1. Water quality monitoring of the groundwater at different spots through the whole aquifer under the Sana'a urban area, which is expected to be polluted due to the cesspits.

Number of samples should be considered is equal to the number of well in the Sana'a plateau.

2. Water quality monitoring of the wastewater effluent from the Sana'a treatment plant.

Number of samples should be considered is on daily basis. Nevertheless a composite samples has to be considered rather than grab samples.

3. Water quality monitoring of the groundwater at different points underneath the irrigated area with groundwater with application of fertilizers.
4. Water quality monitoring of the groundwater at different points underneath the irrigated area with wastewater (without application of fertilizers).
5. Sludge monitoring from the treatment plant. Composite samples on daily basis should be considered

4.2 Proposed parameters

Groundwater underneath the urban area should be analyzed for the presence of NO_3^- and NH_4^+ as indicators for wastewater pollution due to the cesspits.

Groundwater underneath the agriculture area should be analyzed for the presence of Nitrate and Ammonia. The source of nitrate might be due to:
a. Wastewater application or
b. Fertilizer application for the agriculture.
Therefore analysis of N isotopes should be considered to check the source of Nitrate.

Analysis of wastewater from the effluent of the treatment plant should be considered for the following two parameters: Salinity and Boron. These two parameters will have a sever effect on the irrigated soil and plants. Other heavy metals should also be considered in case the industries are discharge into the sewerage systems. All these parameter might also be analyzed for the groundwater quality.

Sludge quality from the treatment plant should be analyzed for Boron and other heavy metals as mentioned early for the wastewater.

The long term analysis for groundwater, wastewater and sludge monitoring is listed in Table 10

Table 10 Long term analysis of groundwater, wastewater and sludge monitoring.

Samples	Groundwater		Wastewater effluent	Sludge
Site	In the urban area	In the agriculture area	WWTP	WWTP
Number of samples	Equal number of wells	Equal number of well	Daily composite samples for two weeks	Daily composite samples for two weeks
Parameters to be analyzed	NO_3^- and NH_4^+	NO_3^- and NH_4^+ (Isotopes)	Boron, Salinity and other heavy metals depending on the industries discharge	Boron, Salinity and other heavy metals depending on the industries discharge

4.3 Recommendations for short-term monitoring

- The excess sludge should be reconsidered and disposed from the final sedimentation tank where the DS is higher in order to achieve higher DS content at the drying beds.

- The effluent from the wastewater treatment plant should be continuously monitored and the 5 days retention of the effluent should always be adopted from the microbial point of view.
- Drip irrigation should be used when using effluent for agriculture to avoid the contact and to save water.
- The southern area of Sana'a city that will be provided with on-site disposal facilities should not use cesspits. Other safer disposal with utilizing the effluent should be adopted.
- The effluent from industries should be controlled based on the specification
- Sludge should be tested and the quality is monitored and only used when it is safe for the agriculture.
- Specific agriculture crops should be planted based on the water and sludge quality.
- Continuous soil and water samples should be monitored from the whole Sana'a and specifically from the places where the pollution was witnessed in order to see the improvement.
- Throughout Sana'a area, at the place were the sewers were constructed, cesspits must be pumped as it is considered a source of pollution.
- For a quick assessment for the applicability of wastewater and sludge for use in agriculture, the following parameters and Table 11 are suggested for wastewater and sludge:

1. Pathogenic Bacteria: Salmonella, Shigella, Vibrio Cholera, Enteropathogenic E. Coli, Mycobacterium, Leptospira and Francisella.
2. Helminth eggs.
3. Fungi (which would cause skin diseases).
4. Heavy metals
5. EC
6. pH
7. N
8. O.M (for sludge only)
9. Na^{+}, Cl^{-}, B^{-}, Ca^{2+} , Mg^{2+}, suspended solids (for wastewater only)

Table 11. The proposed short term sampling points are suggested as follow.

Type of sample	Position	Sampling point	number of samples
Wastewater – (Composite sample)	effluent of the wastewater treatment system	effluent of the final classifiers	sampling every hour and using 2 (duplicate)samples after mixing the 24hr samples
	Retention pond	effluent of chlorination	2 samples
			2 samples
		effluent of the retention pond	2 samples
Sludge (Grap samples)	Thickeners	effluent of the thickeners	2 samples
	Drying beds	after design retention time of the sludge	4 samples
	sludge in the storage	after three month drying	4 samples
		after six months drying	4 samples
		after 12 months drying	4 samples

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