Managing urban water under stress: the case of Sana'a, Yemen

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Abstract

Lack of water management in the Sana'a Basin in Yemen has led to mining of groundwater and massive groundwater quality deterioration. In the last four years, management of wastewater has changed dramatically and entire city neighborhoods have been connected to a conventional sewer system. In this paper, the effects of this measure on long-term groundwater quality development of the aquifers underlying Sana'a and, more specifically, on water quality of the public supply peri-urban wellfields are analyzed. The results, obtained with a transient groundwater model, indicated that by 2020 the construction of the sewerage will have considerably reduced the area polluted by groundwater, but the process is slow. Furthermore, construction of the sewerage will hardly affect the groundwater quality of the wellfields, since flow is not directed towards most of the production wells. The Yemeni authorities should realize that less expensive sanitation alternatives are available, but they need user participation, which, in turn, would raise public awareness that water supplies and sanitation are not to be seen as solely a government responsibility.
Keywords: urban groundwater, waste water management, ground water pollution, pollution control, sustainable water use, groundwater modeling.

1 Introduction

The effects of wastewater infiltration (primary or secondary, diffuse or as a point source) on groundwater quality have been studied at various locations. One of the major problems with on-site sanitation is nitrate pollution of the groundwater. When Foppen [1] used an exploratory one-dimensional transport model of a 200 m column of the aquifer under the urban area of Sana'a, he concluded that upon diffuse infiltration of wastewater the two main hydrochemical processes dominating groundwater quality in this aquifer are nitrification and cation exchange.

Water management in Yemen in the last 2 decades has been characterized by ill-defined ministerial mandates and rules and regulations being made, but not implemented or enforced. This lack of water management has led to severe water scarcity. Also, it has been recognized that water scarcity is being accelerated by massive groundwater quality deterioration, especially in the vicinity of major urban areas, mainly due to the lack of wastewater collection systems. However, in the last four years, in response to the unacceptable health risks, odor nuisance and road damage associated with sewage continuously flooding the streets in some areas of Sana'a, the management of waste water has changed dramatically. As a result, entire city neighborhoods have been connected to the sewerage and a new sewage plant has been built just north of the airport (see Fig. 1).

In this paper we analyze the effect of these measures on trends in the long-term groundwater quality of the aquifers under Sana'a. A groundwater model of the greater Sana'a Basin was constructed with MODFLOW and calibrated using PEST. This transient model was used to analyze conservative contaminant transport (of nitrate) resulting from various water management options.

2 Area description

2.1 Physiography

Sana'a is in the center of the Sana'a Basin (Sana'a Basin catchment boundary is drawn in Fig. 1), an intermontane plain of some 3,200 km^2 in the central Yemen Highlands. The plain is about 2,200 meters above sea level but to the west, south and east is flanked by mountains rising to about 3,000 m.a.s.l. During the last 20 years Sana'a city has grown at an annual rate of around 10%: there were 80,000 inhabitants in 1970, 1,000,000 in 1994 and the current estimate is around 2,000,000 inhabitants. As a consequence, the area of the city has grown tremendously in the last 20 to 30 years.

In the 1980s a sewer system was constructed in the old and densely populated center of Sana'a. The wastewater was collected in sewage ponds a few kilometers north of Sana'a. The coverage of the sewage network was not complete and pit latrines were still very common, especially in the western part of the sewered area. In 2000 a new wastewater treatment facility was built just north of the airport. Since its completion, a large part of the city has been connected to the sewerage. During the previous sewerage construction works in the 1980s households had been given the choice of being connected, but this time no such option was available: connection to the sewerage is mandatory in the greater city center (area within the dashed line of Fig. 1).

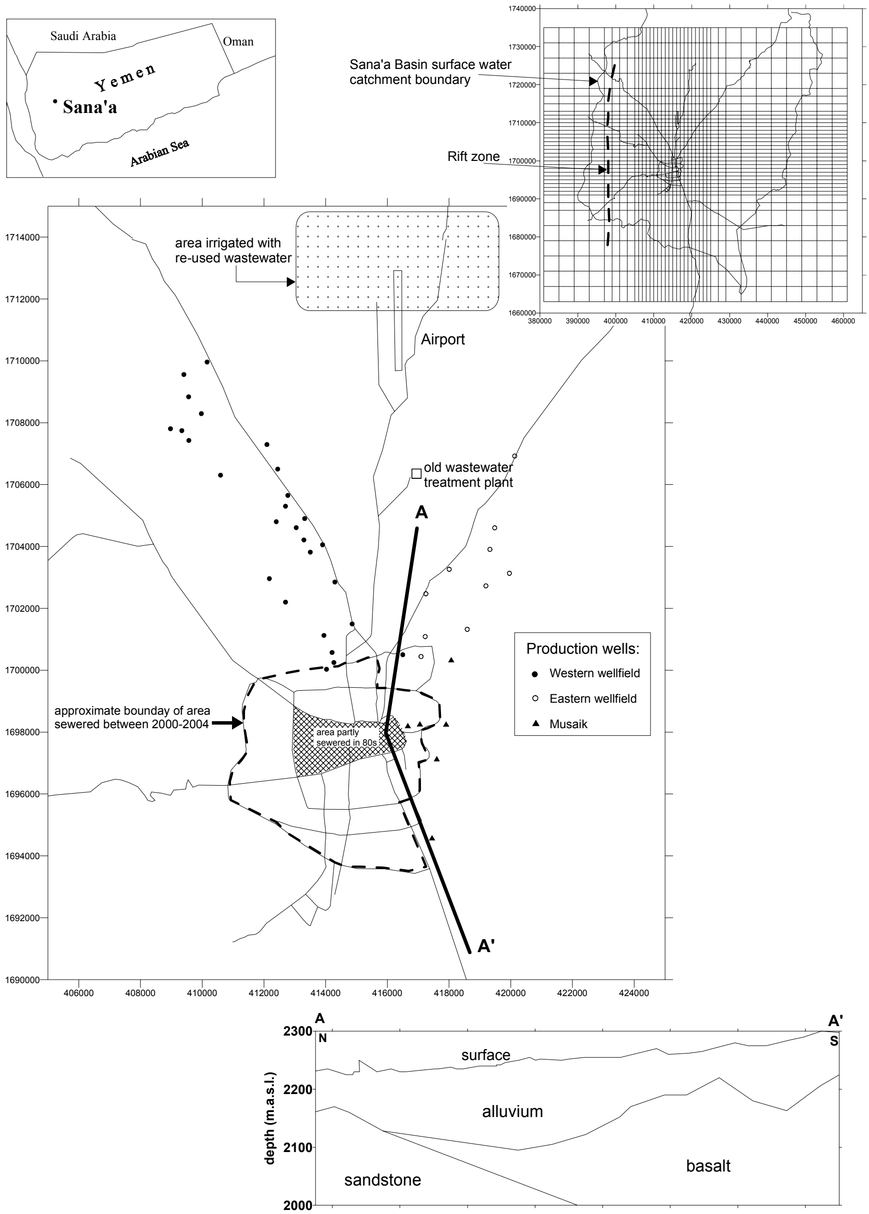

Figure 1: Location map of Sana'a. Upper left: Location of Sana'a; upper right: discretization of the area in 38 rows and 37 columns for the MODFLOW model; lower right: cross-section A-A' showing the most important hydrogeologic formations in the Sana'a Basin.

2.2 Water balance of the Sana'a Basin

The main aquifer in the Sana'a Basin is the Cretaceous sandstone (the Tawilah Formation; see cross-section in Fig. 1), which has a relatively high premeability and secondary porosity. The aquifer is heavily exploited throughout the Basin. In rift zones, the sandstone has been hydraulically "disconnected" by basalt that has erupted to the surface (see Fig. 1, upper right).

The average yearly precipitation in the period 1972-1990 was 235 mm. Infiltration of surface flows in ephemeral wadis is believed to be the most important and least predictable component of recharge from precipitation in the Sana'a Basin (Alderwish and Dottridge [2]). Mean recharge in the Sana'a Basin is estimated at 4-8% of the precipitation measured at Sana'a. The volume of groundwater abstracted from the aquifers in the Sana'a Basin was estimated during a number of well inventories in the Sana'a Basin (in 1973, 1984, 1994-1995 and in 2001). The total number of wells has grown from a few hundred in 1973 to around 6000 in 2001, while the abstracted volume has grown from 60 Mm^3/yr to 370 Mm^3/yr. Of this amount, around 85% is for agricultural use. The main irrigated crops are the cash crops qat and grapes (Hamdi [3]). Around half of the domestically used water is supplied by wellfields around the city that are controlled and maintained by the public supplier. The most important are the Western wellfield, the Eastern wellfield and the Musaik wellfield (see Fig. 1). The other half is supplied by the private sector, which sells water in bottles, jerry cans or tankers. Alderwish and Dottridgde [2] estimated that 59% of the water used for domestic supply infiltrated via cesspits into the urban aquifers as wastewater. Hamdi [3] estimated the total volume of wastewater infiltration in the city in 1995 was 10-20 Mm^3.

As a result of the rapid and more or less uncontrolled increase in the number of wells and volume of abstracted water, water tables have fallen drastically. In the sandstone aquifer the rate of decline since the early 1970s has varied from place to place and has ranged from 1.5 to 4 m/yr.

2.3 Hydrochemistry of the urban aquifers

Groundwater in the aquifers below Sana'a typically has high concentrations of almost all major cations and anions (Foppen [1]). The $[NO_3^-]$ ranged from 1-3 mmol/l, while NH_4^+ was absent (see Fig. 2). Upon infiltration of wastewater from cesspits to the saturated zone nitrification occurs, whereby NH_4^+ is oxidized first to NO_2^- and then to NO_3^-. However, the $[NO_3^-]$ in groundwater was far less than the average $[NH_4^+]$ in wastewater (10 mmol/L), indicating that there is a sink for N species between the cesspit and the saturated zone. Besides the effects of dispersion and diffusion on $[NO_3^-]$, the most likely sink is cation exchange of NH_4^+.

3 Methods

3.1 Model set-up

The model area (see Fig. 1) covers some 6,400 km^2, half of which consists of the Sana'a Basin (3,200 km^2). The aquifer system was schematized into 3 separate model layers (Alluvium, Volcanics, and Sandstone). Initial horizontal permeability estimates were obtained from a limited number of pumping tests carried out in the vicinity of the Western and Eastern wellfields (data not given).

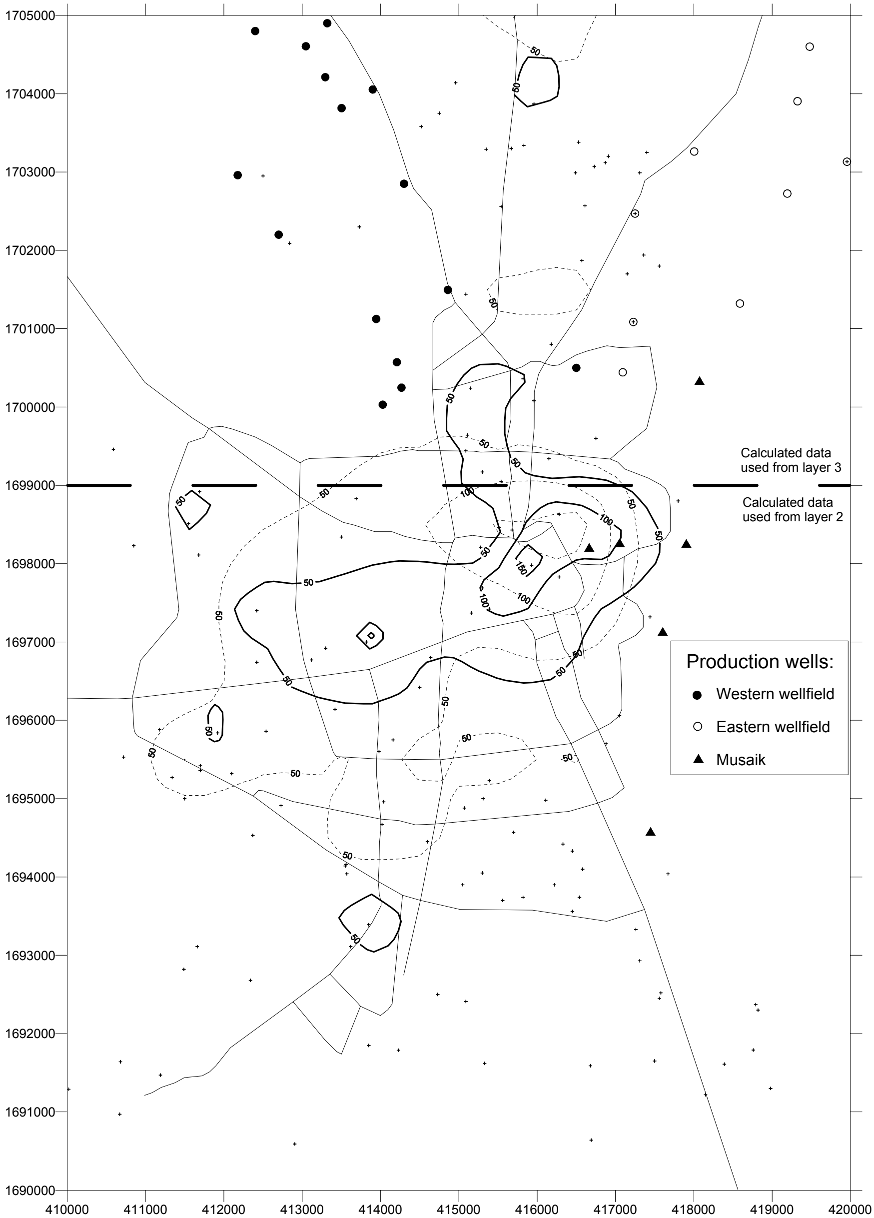

Figure 2: Nitrate concentration in the aquifers below Sana'a in 1995 (in mg/L; solid lines: measured; dashed line: calculated).

The steady state model was calibrated for the year 1972 with the head data from Italconsult [4]. The transient model was calibrated with the well-inventory data from 1984 (Mosgiprovodkhoz, [5]), and with 20 hydrographs of observation wells within the Western and Eastern wellfields covering the period 1972-1995 (monthly observations). With the calibrated flow files, conservative transport of nitrate was simulated. Recharge wells were located in the top layer to simulate wastewater infiltration and were assigned an average value for $[NO_3^-]$ of 248 mg/L (= 4 mmol/L). Calibration was carried out by comparing calculated nitrate values with measured nitrate values (data from 1995; Foppen [1]).

3.2 Scenario calculations

To evaluate the effect of the construction of the sewerage on groundwater quality we modeled two scenarios for the period 2005-2020. In the first scenario (called 'laissez faire') uncontrolled infiltration of wastewater in the city was assumed to continue at the same rate as in 2000. In the second scenario (called 'sewering the city center'), the uncontrolled infiltration of wastewater in the city was stopped by eliminating all recharge wells in the city in model layer 1 in the year 2000 and onwards. In this case, sewage originating from the city was allowed to infiltrate north of the airport near the location of the new wastewater treatment plant (see Fig. 1). We realized that the area sewered in the model (the entire city) was larger than the area actually sewered by 2004. However, we felt this was justified, as the Yemeni authorities intend to continue expanding the sewered area for at least the next few years.

Near the location of the new wastewater treatment plant, a scheme for re-use of wastewater for agricultural purposes was anticipated with an area extent of some 21 km^2 (see Fig. 1). We assumed re-use would not be very efficient: 75% of treated wastewater leaving the new wastewater treatment plant was allowed to infiltrate into the aquifers again. Furthermore, the model assumed that as a result of wastewater treatment the $[NO_3^-]$ of the 75% of treated wastewater leaving the plant was half (124 mg/L) of the $[NO_3^-]$ of untreated wastewater infiltrating into the aquifers (248 mg/L).

4 Results

4.1 Calibration

The Root Mean Squared (RMS) error between measured and calculated heads for the steady state calibration was 25 m (179 pairs of values) and for the transient model was 63 m (292 pairs of values). Given the magnitude of the change in heads over the entire modeled area (around 1000 m), these values were considered to be acceptable.

Calculated nitrate concentrations in layer 2 (south of the line Y = 1 699 000) and layer 3 (north of the same line) were combined and compared with measured nitrate concentrations in drilled wells in 1995 (see Fig. 2). Since the wells had mainly been drilled to depths between 200 and 400 m, in order to accurately compare values the two (southward dipping) layers were combined into one map. The calculated nitrate values agreed reasonably with measured values in terms of maximum concentration (maximum contour line in both cases is 150 mg/L) and in terms of extent of the area affected by sewage infiltration. However, there were a number of differences between calculated and measured nitrate values which were mainly caused by variations in actual sewage infiltration rate and/or variations in infiltrating nitrate concentrations.

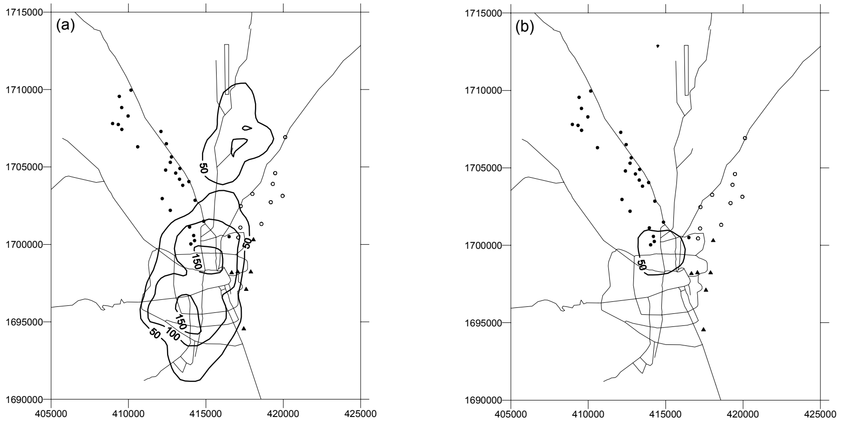

Figure 3: Calculated nitrate concentration in the aquifers below Sana'a in 2020 (a: laissez faire; b: sewering the city center).

4.2 Managing the urban aquifers: laissez faire and sewering the city center

In the laissez faire scenario, nitrate concentrations in the aquifer exceeded 50 mg/L throughout the entire urban area, with maximum values of around 150-200 mg/L (Fig. 3a). In the sewering the city center scenario, nitrate concentrations fell considerably, to less than 50 mg/L throughout the city and with maximum values around 70 mg/L just north of the city center (Fig. 3b). So, remediation of the aquifer complex occurred, but the process is slow and it will take decades before contaminant concentrations have fallen to acceptable levels.

With regard to the averaged nitrate concentration of each wellfield, in the laissez faire scenario (Fig. 4a), mixing the entire abstracted volume caused the nitrate concentration to increase only slightly from around 15 mg/L in 2005 to 20 mg/L in 2020 ('mixture' in Fig. 4a). This surprisingly slow increase was mainly due to the slow increase in nitrate concentration in the Western and Eastern wellfields, the main suppliers of drinking water in Sana'a. This was because the direction of flow out of the city was due north and therefore most of the production wells were not affected by the contaminant plume. Furthermore, production wells in these wellfields tap the Tawilah sandstone aquifer (layer 3) and due to the relatively high porosity of the sandstone, pore water flow velocities are relatively low. Therefore, nitrate concentrations increased only very slowly. In the Musaik wellfield, which abstracts water from the Volcanics (layer 2), the averaged nitrate concentration was higher, not only due to the proximity of the production wells to the city, but also due to the layer's relatively low porosity and high pore water flow velocity. In the sewering the city center scenario (Fig. 4b), the rising trend stopped and the nitrate concentration remained more or less constant (see 'mixture' in Fig. 4b) at around 12-13 mg/L in the period 2005-2020.

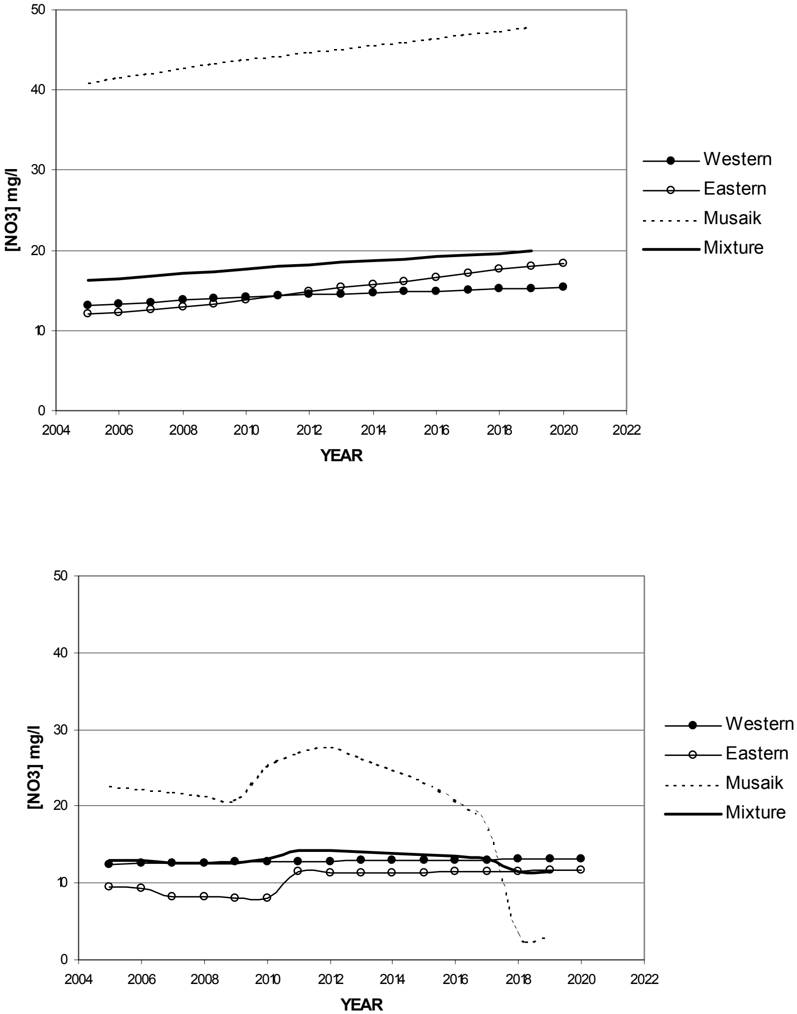

Figure 4: Development of nitrate concentration in the wellfields, determined as the weighted average of all production wells per wellfield and as the weighted average of the three wellfields ('mixture'; a (above): laissez faire; b (below): sewering the city center).

5 Discussion

What are the advantages and disadvantages of the sewerage construction? Prolonging the lifetime of the public supply wellfields (Western, Eastern and Musaik wellfields) does not seem to be an advantage of the construction of the sewerage. The only (and very important) advantage is the reduction of health risk for the population of Sana'a. In the past, in a number of areas throughout the city cesspits became clogged very frequently and sewage flooding the streets with associated health risks, odor nuisance and road damage were facts of life in those areas. Nowadays, sewage flooding the streets does not occur any more.

However, there seem to be three important disadvantages of the sewerage. In the first place a decline of the phreatic water table of some 20-40 m has occurred in the Quaternary Alluvium. As a result, the average daily yield of many dug wells has fallen sharply. Nowadays most of those wells abstract water for only 1-2 hours per day, whereas this used to be 10-18 hours. This could have serious consequences for the agricultural yield of the so-called awqaf (single: waqf), which are abundant in Sana'a. A waqf is a small plot of agricultural land (usually less than one hectare) including a number of houses and a mosque. In Islamic culture the word waqf has the meaning of holding certain property and preserving it for the confined benefit of certain philanthropy and prohibiting any use or disposition of it outside that specific objective. Usually each waqf has a dug well, which is used for ritual ablution, domestic purposes and irrigation. The socio-economic consequences of a drastic decline in agricultural yield of the awqaf could be substantial, since a certain part of the population in the older parts of Sana'a seems to rely on these agricultural plots.

A second disadvantage of the sewage network is that there is hardly any control over the re-use of the enormous supply of treated water north of the airport. According to Hamdi [3], the uncontrolled re-use of treated sewage will not have any beneficial effect on sustainable (renewable) water resources management. It will merely increase agricultural demand for water, as the treated sewage is commonly used by farmers who cannot afford facilities to abstract groundwater. Furthermore, a lack of control in combination with a lack of knowledge of proper wastewater re-use might lead to environmental degradation, soil salinization, and adverse public health effects (dissemination of waterborne diseases).

A third disadvantage is that construction of a sewage network is a very expensive option that requires maintenance, both financially and technically. From other urban areas in the world it is known that conventional sewerage is by far the most expensive option. Furthermore, conventional sewerage is basically a water-driven system that performs best at high specific water consumption rates (preferably over 70-80 l/c/d). In view of the critical situation with respect to water resources availability within the Sana'a Basin, it was probably unwise to consider the citywide application of conventional sewerage.

In our opinion, a wastewater-holding tank with an overflow construction to small-bore sewerage could be considered as a serious alternative to the conventional wet off-site sanitation, especially in the areas of basalt outcrops.

This type of sewerage is cheaper than conventional sewerage and also easier to construct in areas of basalt. However, for small-bore sewage systems to function effectively, there must be user participation, as the system's performance relies on changes in domestic habits and practices, and a fair degree of local care being taken by the beneficiaries. Therefore, in addition to saving money, another benefit would be that this type of sanitation would help raise the awareness of Sana'a citizens that water supplies and sanitation are crucial to the sustainability of their society, and thus are not to be seen as solely the responsibility of government.

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