PART Ⅱ : COUNTERMEASUREMENTS FOR THE GROUNDWATER CONTAMINATION

CHAPTER 13 ENVIRONMENTAL COUNTERMEASURES

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Part I of this report presents the results of the investigation and documents the groundwater and soil contamination in the Sohar mine area caused by high salinity and heavy metals. Based on these results, mitigation countermeasures are urgently needed to address the upstream contamination sources and prevent the diffusion of contaminants to the downstream areas of Wadi Suq.

The environmental countermeasures along Wadi Suq are divided into two districts as shown in Figure 13.1, including district between the tailing dam and Subarea 1 and district between Subarea 1 and Subarea 3 to 5. Each district of the groundwater contamination countermeasures of Wadi Suq, which is the main purpose of this Feasibility Study, is examined in the following sections of this report.

13.1 Countermeasures for the Water Quality

Countermeasures addressing water contamination between the tailing dam and Trenches-1 and -2 in Subarea 1 have been proposed by OMCO. OMCO's countermeasure plan was proposed to and accepted by the Government of Oman. Construction of the on-site evaporation pond prescribed under this plan has already commenced.

OMCO's contamination countermeasure plan was reviewed in this Study and re-examined including alternatives for the contamination countermeasures.

13.1.1 Contamination Potential in the Tailing Dam

The tailing dam is the primary source of salinity and heavy metal contamination in the Wadi Suq basin. The diffusion of salt and heavy metal contaminants from the tailing dam is proceeding to the downstream areas of Wadi Suq and will certainly continue in the future.

Although the tailings have a maximum acid potential of approximately 650 t of $CaCO_3$ equivalent per 1,000 t of tailings, seepage water from the tailings dam remains nearly neutral due to neutralization of lime mixed into the tailing dam. However, it is possible that acidic metal-laden drainage from the tailing dam may occur in the future due to depletion of the neutralizing capacity of the lime in the tailing dam and the calcreted layers that lie beneath the tailings and downstream of the wadi.

Therefore, the contamination countermeasures in the tailings dam to Trench-1 and -2 (Subarea 1) are very important for reducing or eliminating the source of contaminants in this district.

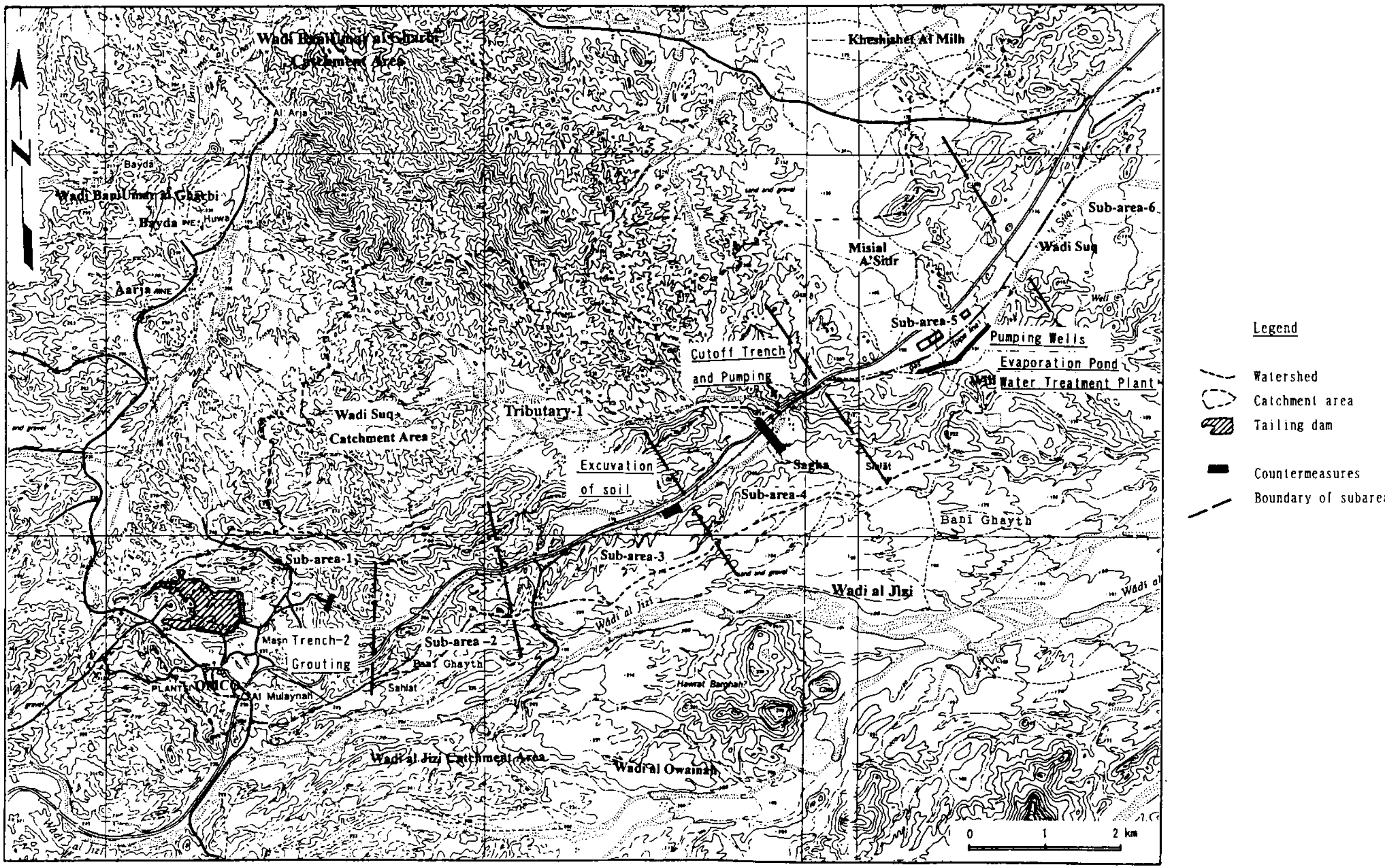


Figure 13.1 Location of Mine Pollution Countermeasures along Wadi Suq

13.1.2 OMCO's Contamination Countermeasures

In 1999, OMCO prepared a plan for ending the practice of recycling seepage collected in Trenches-1 and -2 and capping the tailing dam with a bitumen liner material as a method of preventing further infiltration of rainwater into the tailings. The purpose of this plan is to reduce or eliminate seepage coming from the dam, thereby mitigating the dam as a source of groundwater contamination.

OMCO's countermeasure plan (Figure 13.2) is summarized as below.

- The practice of returning Trenches -1 and -2 seepage to the tailing dam would be ended. Instead, the seepage from the trenches would be pumped to an on-site evaporation pond constructed below the dam. The pond would receive an estimated 50,000 m^3 of seepage per year. As shown in OMCO's design package, the pond would cover approximately 32,600 m^2 (3.26 ha). The evaporation pond would be lined with a 2 mm flexible HDPE geo-membrane to prevent leakage. The location of the evaporation pond relative to the tailings impoundment is illustrated in Figure 13.2.
- Under OMCO's plan, the tailings in the tailing dam would be re-contoured to provide drainage in an easterly direction (The tailings currently slope approximately 1 to 2 % toward the north.). The re-contoured surface of the tailings would be sloped at 0.2 % so that any rainfall would drain off the tailings, be collected in lateral drainage ditches, and conveyed to Wadi Suq to the east of the dam. By the JICA team's estimate, attaining the slopes indicated in OMCO's design drawings would require cutting and filling approximately 1.3 million m^3 of tailings.
- After re-contouring the surface, the tailings would be capped with a 4 mm bitumen liner material.

13.1.3 Contamination Countermeasure alternatives of the Tailing Dam

(1) Countermeasure Alternative -1 : Groundwater Pumping and Disposal

JICA's Countermeasure Alternatives consist of Alternative-1 (installation of de-watering by pumps) and Alternative-2 (Capping the tailings; Alternatives-2A, 2b and 2C).

Countermeasure alternatives of the Tailing Dam		: No. of Countermeasure Alternatives
1)	Groundwater Pumping and Disposal	: Alternative-1
2)	Capping the tailings	: Alternative -2A
		: Alternative -2B
		: Alternative -2C

The specific actions proposed under Alternative-1 include the following:

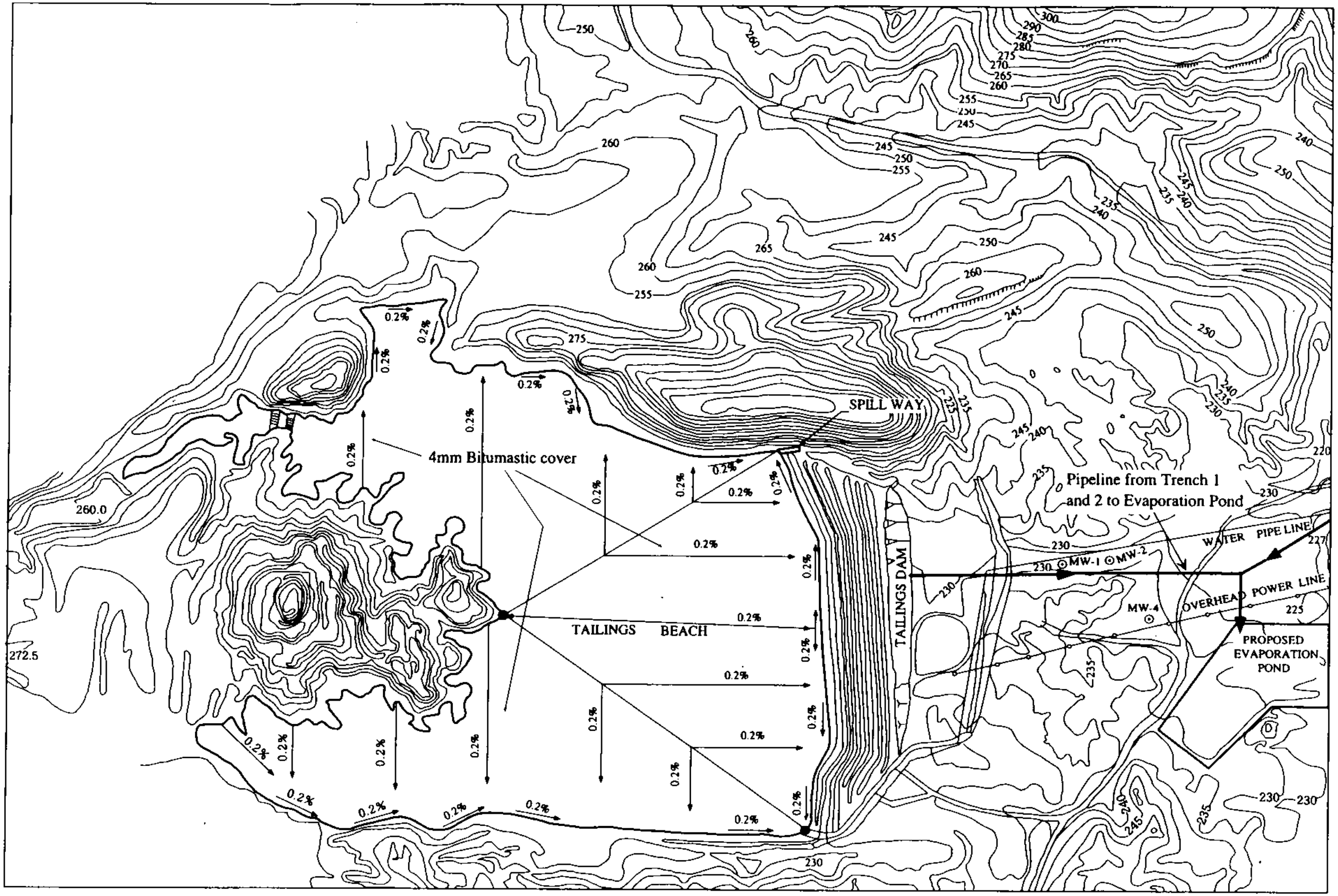


Figure 13.2 OMCO's Plan for Capping the Tailing Dam and Evaporation Pond

- As in OMCO's plan, the practice of returning Trenches -1 and -2 seepage to the tailing dam would be ended. The seepage collected from the trenches would be pumped to the on-site evaporation pond constructed below the dam, as described under OMCO's plan. The volume of seepage collected by the trenches is expected to decrease with time as this alternative is implemented.
- The surface of the tailings would be left in its current state. However, a system of lateral drainage ditches and detention dams would be constructed to prevent rainfall running onto the tailings impoundment from the estimated 1.01 km^2 catchments area that lies upstream of the tailings impoundment. These drainage ditches would collect runoff from the hills to the west and north of the tailing dam and convey it to the north.
- A system of groundwater extraction wells would be installed to extract the groundwater in the tailings, thereby de-watering the tailings and eliminating the source of seepage to the low portions of Wadi Suq. The wells would be installed as illustrated in Figure 13.3. The locations of the wells, shown in Figure 13.3 correspond to the former natural drainage channels, which are now buried under the tailings. The former drainage channels would be tapped by the extraction wells at the topographic low points under the tailings. It is presumed groundwater may still be migrating through these buried natural drainage channels.
- The groundwater extraction system proposed under Alternative 1 would consist of 19 extraction wells installed to an average depth of approximately 40 meters below the tailings surface. Each well would be equipped with an electric submersible pump with level controls designed to activate and deactivate the pumps at set water levels. Because the tailings are fine grained and exhibit low permeability, the wells are expected to produce a low volume of extracted groundwater. The combined total volume of water extracted from the wells is estimated at approximately 61 m^3 per day, or 22,300 m^3 per year
- Extracted groundwater would be pumped to the evaporation pond.
- To prevent wind mobilization of the tailings, the entire surface of the tailings would be covered with 30 cm of soil and armored with stones to prevent wind erosion.

(2) Countermeasure Alternative -2 : Capping with Engineered Covering Systems

Alternative-2 addresses seepage from the tailing dam by cutting off infiltration and off-site surface water run-on by capping the tailings with a permanent engineered covering system. The covering system would be designed to reduce or eliminate the source of the seepage, which is rainfall and storm water running onto the tailings from off site. The details are described as below.

- As in Alternative-1, the recycling of seepage from Trenches 1 and 2 would stop under this alternative. The seepage collected in the trenches would be pumped to the evaporation pond described under OMCO's plan. It is anticipated that the seepage volume being pumped to the evaporation pond will decrease following implementation of Alternative-2 because infiltration would be eliminated.
- The surface of the tailings would be prepared for capping by simply rough grading and compacting.

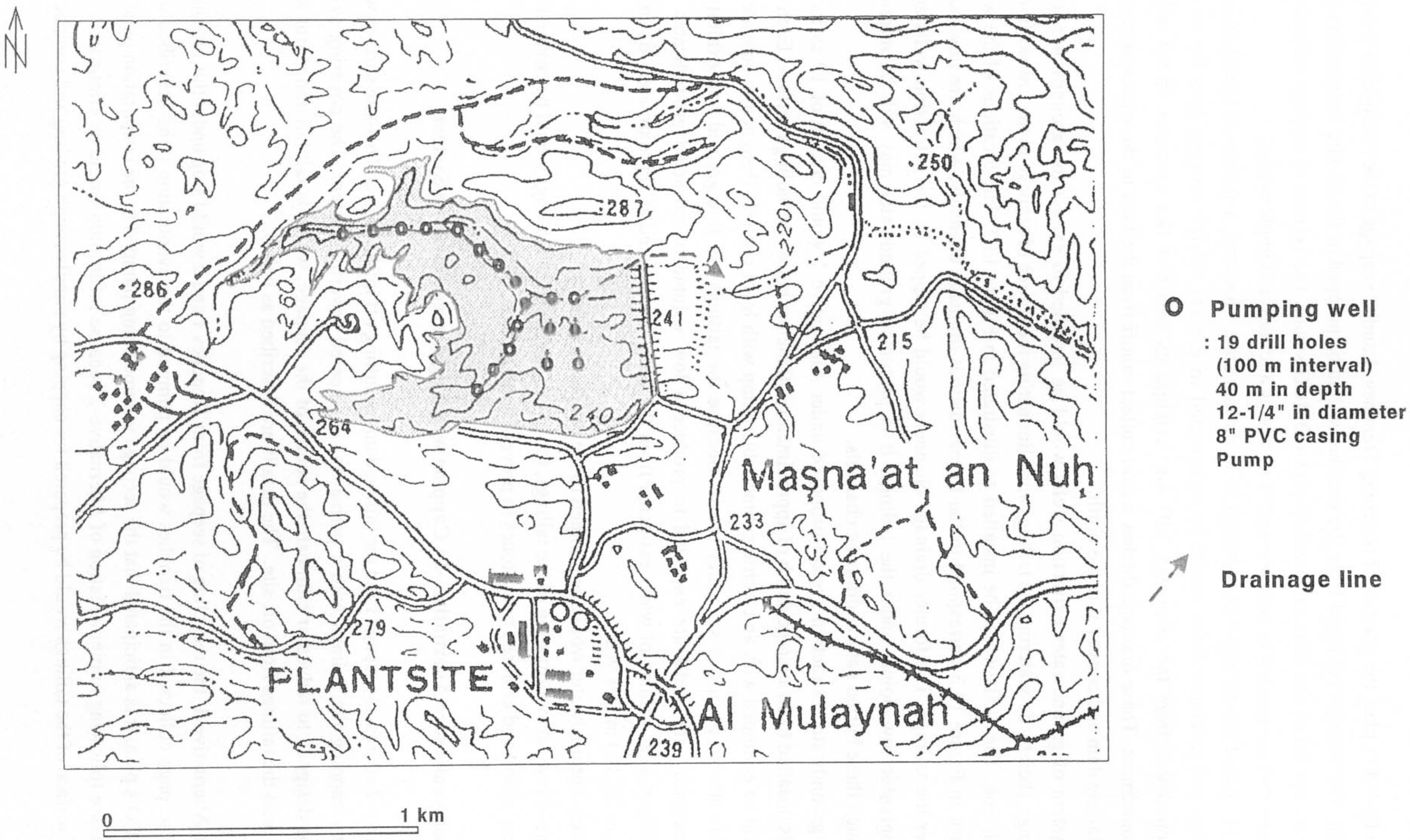


Figure 13.3 Pumping Plan in the Tailing Dam

The existing topography of the surface would be left unchanged. The existing topography would be maintained to promote drainage to the north, away from Wadi Suq.

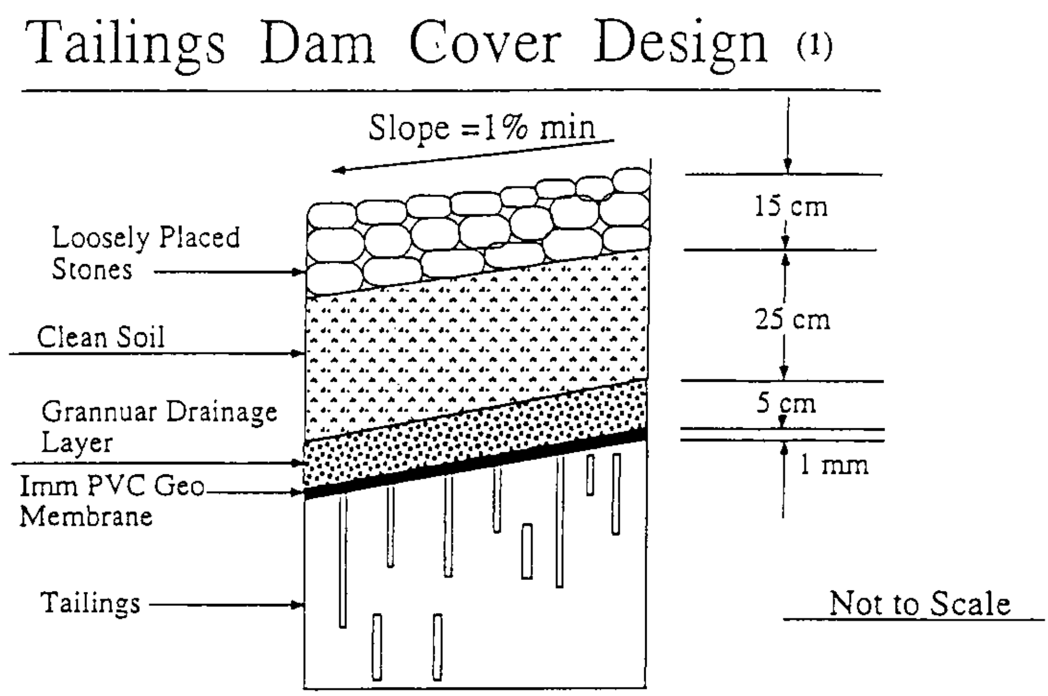
- Several capping scenarios are presented as part of Alternative-2, as follows:
  A. Under Alternative-2A, the surface of the tailing dam would be capped with the permanent engineered composite cover system illustrated in Figure 13.4. This cover system would consist of a sand layer which would act as bedding for the subsequent layers, an impermeable geomembrane consisting of 1 mm solvent-welded PVC liner material, a soil layer consisting of 30 cm of native pit run soils placed over the PVC liner, and - 15 cm layer of rock armoring the soil layer to prevent wind erosion of the soil layer.
  B. The same composite cover prescribed for Alternative-2A would also be used under Alternative-2B.
  C. Under Alternative-2C, the tailings would be capped with a simple 50 cm soil cover placed directly over the tailings and armored with a 15 cm layer of loosely placed stones. The conceptual design for this soil cover is illustrated in Figure 13.4.
- Three separate drainage scenarios are proposed under Alternative-2, as follows:
  A. Under Alternative-2A, a drainage channel would be constructed to link the tailing dam with tributaries to Wadi Bani Umar al Gharbi. Rainfall and surface water running onto the capped tailings would flow by gravity to the topographic low point in the tailing dam and would then by conveyed by the drainage channel north to Wadi Bani Umar al Gharbi.
  B. Under Alternative-2B, no drainage channel would be constructed. Instead, rainfall and surface run on would collect on the liner surface at the topographic low point. The water would be allowed collect during the wet seasons and would evaporate during the dry seasons of the year. The impermeable layer of the cover system would prevent infiltration.
  C. Under Alternative-2C, a system of lateral drainage ditches and detention dams would be constructed to prevent rainfall from running onto the tailings impoundment from offsite. These drainage ditches would collect runoff from the hills to the west and north of the tailing dam and convey it to the north, as in Alternative-1.

13.1.4 Evaluation of Countermeasure Alternatives

This section presents the evaluation of countermeasure alternatives proposed for the tailing dam. The tailing dam alternatives are compared on the basis of their cost, long-term effectiveness, and implementability (Table 13.1).

(1) Cost Evaluation

This section presents the evaluation of countermeasure alternatives for the tailing dam based on the capital construction and long-term operation and maintenance (O&M) costs. Cost data for each of the three alternatives is summarized in Table 13.2. It is also emphasized that the estimated cost of constructing and operating the evaporation pond is not included in the comparison of alternatives



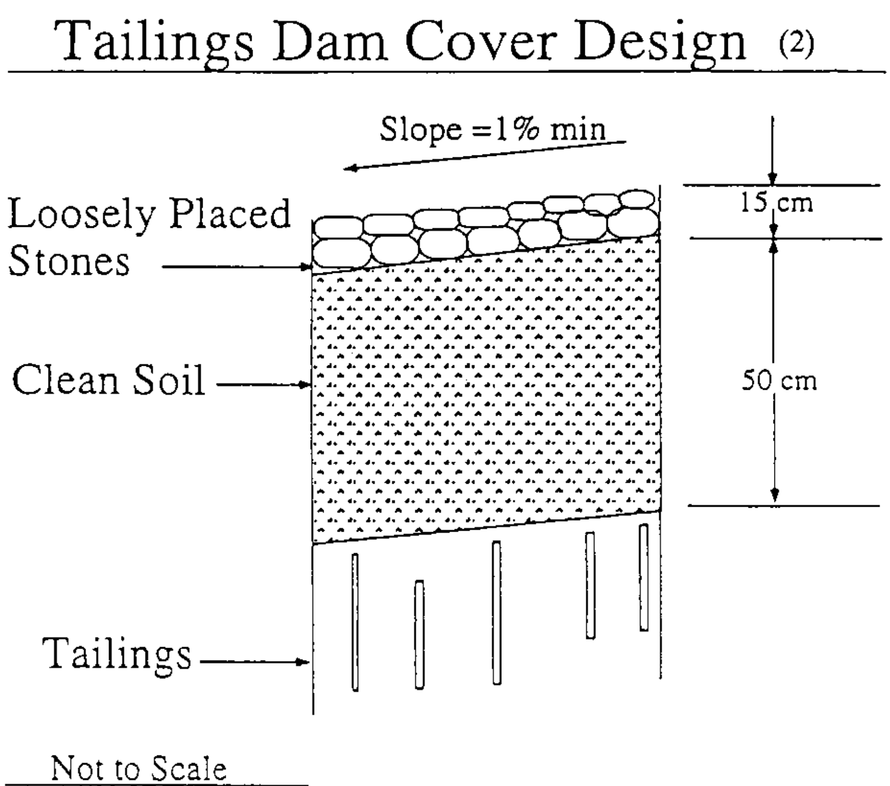


Figure 13.4 Cover Design in the Tailing Dam

Table 13.1 Evaluation of Tailing Dam Alternatives for Effectiveness, Implementability, and Cost

Alternative	Effectiveness	Implementability	Cost
OMCO Plan	Initially, OMCO's plan will effectively eliminate infiltration will significantly reduce seepage from the dam. However, this is not a permanent remedy because the proposed bitumen liner will require replacement in the future, unless covered by a protective soil layer.	Implementation of this alternative will require moving a large volume (1.3 million m^3) of tailings. The acidic condition of the tailings may pose risks to workers. Installing the bitumen liner will be labor intensive. The design slope of 0.2% is nearly impossible to achieve. Also, the tailings may continue to consolidate after re-contouring.	The net present value of this alternative is extremely high due to the volume of tailings that would be excavated and filled to achieve design slopes, the high initial cost of the bitumen liner, and the future replacement costs of the liner.
Alternative 1	The estimated pumping rate for the extraction wells under Alternative 1 is less than the estimated infiltration rate. Hence, seepage from the dam may continue to occur despite the pumping. Pumping will be required continuously into the future to deal with rainfall that will continue to infiltrate the tailings. If pumping stops in the future, seepage will begin to occur again.	This alternative is implementable using readily available technology. However, the corrosive nature of the tailings and groundwater in the tailings will create maintenance problems. Pump replacement costs are expected to be high.	The net present value of Alternative 1 is in the middle of the range of tailings dam alternatives. However, O&M costs will continue beyond the 20 year time period used for the cost analysis of this alternative.
Alternative 2A	This alternative is expected to eliminate surface infiltration, thereby eliminating seepage from the tailings dam. The proposed capping design is expected to be permanent with no replacement needed in the future. Eliminating infiltration will have beneficial effects on water quality in both Wadi Suq and Wadi Bani Umar al Gharbi.	This alternative is readily implementable with available materials and technologies. Little or no long-term O&M is required in the future.	The net present value of this alternative is high compared to other JICA alternatives due to high initial capital costs. However, the cost of this alternative is approximately ¼ the present value of OMCO's proposed plan.
Alternative 2B	This alternative is expected to be as effective as Alternative 2A. The cover system is the same as proposed in Alternative 2A and is expected to perform equally as well. However, water ponded on top of the cover system may result in degradation of the cover system over a long period of time, say 50 to 100 years.	This alternative is readily implementable with available materials and technologies. However, some long-term maintenance may be required in the future.	The cost of this alternative is slightly less than Alterantive 2 A but the long-term effectiveness may also be diminished slightly.
Alternative 2C	According to hydrologic modeling results, this cover design is almost equally effective as Alterantives 2A and 2B. However, some infiltration would occur under this alternative.	This alternative is readily implementable with available materials and technologies. Long-term maintenance of the drainage channels would be required.	This is the lowest cost alternative proposed for the tailings dam.

because the pond is required to be built, operated, and maintained under each alternative.

Table - 13.2 Cost Comparison of Tailing Dam Countermeasure Alternatives

Alternative	Estimated Capital Cost (US$)
OMCO Plan	16,084,000
Alternative-1	9,000,000
Alternative-2A	12,000,000
Alternative-2B	12,000,000
Alternative-2C	6,000,000

(2) Evaluation of Countermeasure Alternatives for the Tailing Dam

Although five alternatives of the contamination countermeasures for the tailing dam were examined in this report, the construction work of countermeasures has already been commenced. Therefore, it is obliged to select OMCO's alternative.

From the viewpoint of implementability, it is necessary to re-examine the basic plan of countermeasures of the tailing dam, i.e. design slope (0.2%) of surface of the tailings is nearly impossible to achieve, deformation due to consolidation in the tailing dam may continue, etc. In addition, it is necessary to take care about the working conditions during removal of the tailings because of scattering of the fine-grained tailings.

13.2 Contamination Countermeasures along Wadi Suq

The location of the countermeasure alternatives along Wadi Suq consist of the Subareas 1, 3, 4, and 5 as shown in Figure 13.1. The countermeasure alternatives of the Subareas 1, 3, 4, 5 and water treatment of the contaminated groundwater consist of 7 alternatives, shown as below.

Countermeasure Alternatives	:	No. of Alternatives
・Subarea-1	:	Alternative -3
・Subarea -3	:	Alternative -4
・Subarea -4	:	Alternative -5A Alternative -5B
・Subarea -5	:	Alternative -6
・water treatment of the contaminated groundwater	:	Alternative -7A Alternative -7B

13.2.1 Contamination Countermeasures of the Subarea 1 (Alternative-3)

Trench-2 is installed by OMCO at the end of the Subarea 1 (Figure 13.1). Cutoff concrete wall and curtain grouting into the bedrock was implemented. But the curtain grout was not sufficient, so that the leakage of contaminated groundwater occurred through the weathered zone of bedrock. This is thought to be one of the reasons why the groundwater contamination is now extending to the downstream areas of Wadi Suq. The result of simulation analysis of the contaminated groundwater along Wadi Suq (refer to Chapter 7.) indicate that groundwater contamination will continue into the future if no countermeasures are implemented at Trench-2.

Therefore, in order to enclose of the contaminated groundwater between the tailing dam and Trenches-2 and to improve the groundwater quality on the downstream of the Trench-2, cutoff of contaminated groundwater at trench-2 becomes most important. The contamination countermeasures are limited to the grout method (Alternative-3) on the downstream side of trench-2 as shown in Figure 13.5.

(1) Content of the Grouting Work

The content of the grouting work is shown as below.

1) Location of grouting : downstream side and both wings of the Trench-2
2) Drilling survey : 30m/hole, 10 drill holes : Total depth 300m
3) Specification of grouting work
   - Width of grouting : 200m
   - Number of grouting line : 5 lines
   - Number of grouting holes : 500 holes
   - Total depth of grouting holes : 20m/hole, 10,000m
   - Diameter of grouting holes : 60mm, casing diameter : 152mm
   - Interval of each hole : 2m interval
   - Grouting depth : 10 – 20m deep; Calcrete layers and basalt
4) Equipments
   - Boring machines for survey : Rotary type : 2 sets
   - Boring machines for grouting : Rotary type : ODEX method 2 sets
   - Lugeon test : Packer type, pump

(2) Work schedule

The work schedule of the grouting work is shown in Table 13.3. The construction period is about 7 months.

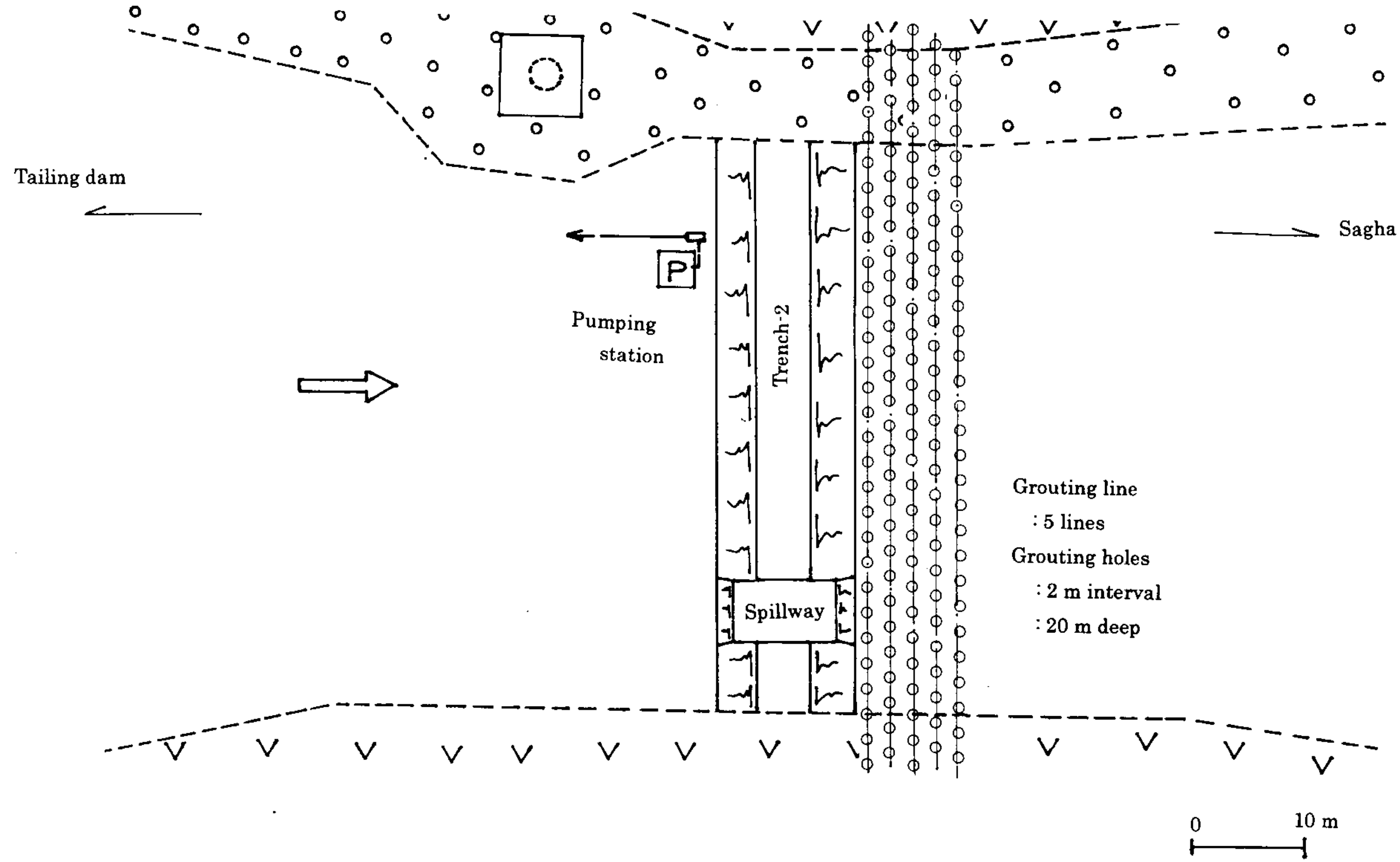


Figure 13.5 Conceptional Grouting Plan at Trench-2

Table 13.3 Work schedule of the Grouting Work

Items (Month)	1	2	3	4	5	6	7	Remarks
1. Preparation・mobilization	━							
2. Drilling investigation	━	━						
3. Grouting work		━	━	━	━	━		Curtain grout
4. Lugeon test		━	━	━	━	━	━	
5. Demobilization							━	

(3) Cost Estimation

Total cost for the grouting work at Trench-2 is estimated US$1,700,000, shown as below.

1)	Drilling investigation	US$ 70,000
2)	Grouting	US$ 1,630,000
	Total	US$ 1,700,000

(Cost includes overhead expenses, contingencies and miscellaneous expenses.)

13.2.2 Contamination Countermeasures of the Subarea 3 (Alternative-4)

Subarea 3 consists of the approximately 2.5 km of the Wadi Suq main channel from the 6.2 km point to the drill hole DH-3 (Figure 13.1). The principal concern in Subarea 3 consists of salt-laden soils resulting from prolonged leakage of seawater from pump station (PS-2) in the vicinity of drill hole DH-3 (Figure 13.6). The seawater releases in this area are documented in the 1995 Ministry of Water Resources report on Wadi Suq. The JICA team identified these salt contaminated soils as a significant secondary source of groundwater pollution in the wadi. The contaminated soil at PS-2 is affected only by seawater without any heavy metals, so that it is different from the contamination derived from the tailing dam.

The contaminated soil at PS-2 will continue to affect to the groundwater downstream of Wadi Suq, if no countermeasure are implemented. Therefore, it is necessary to remove contaminated soil and to improve the groundwater quality.

Contamination countermeasures at PS-2 are limited to excavating the contaminated soil (Alternative-4).

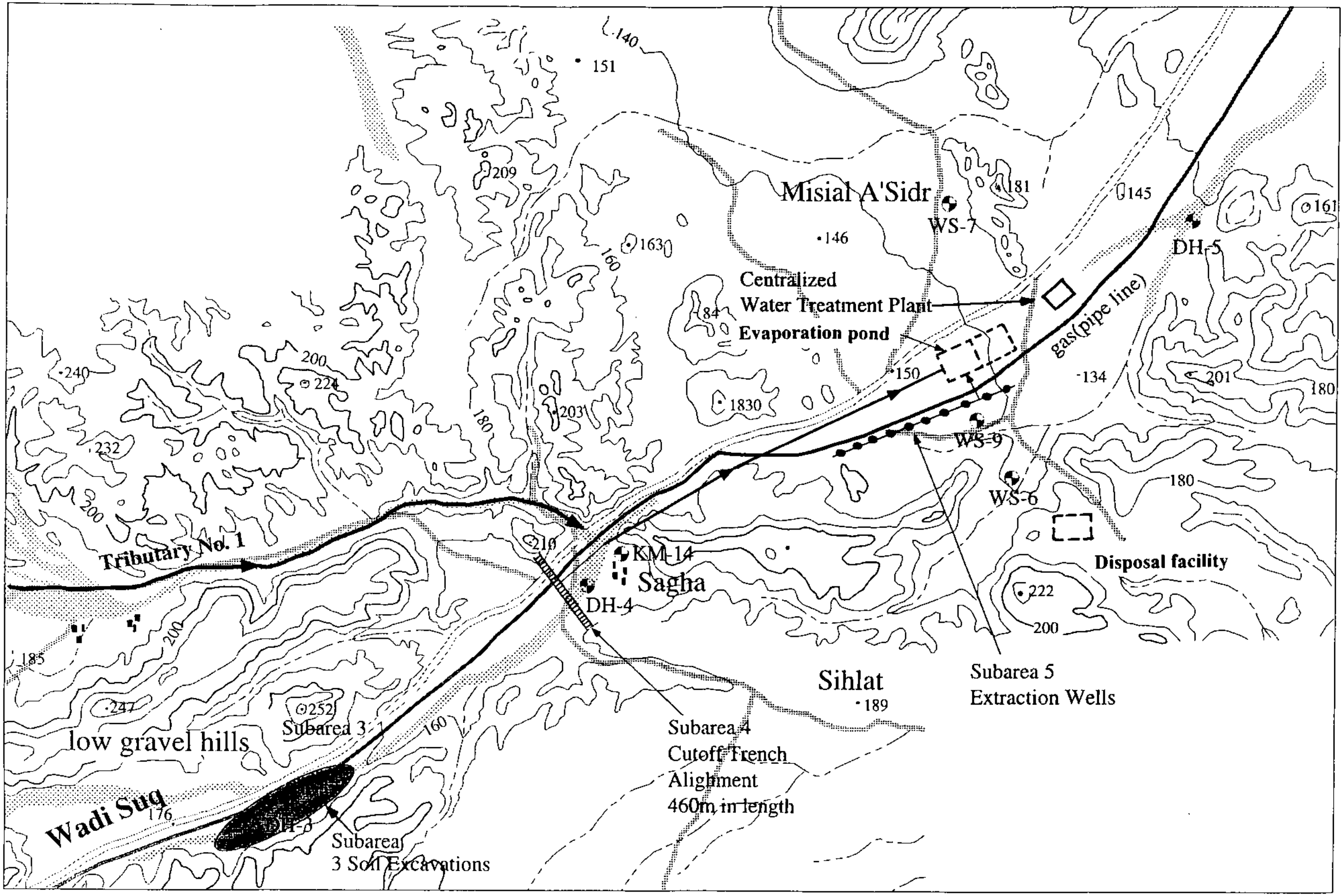


Figure 13.6 Contamination Countermeasures of Wadi Suq Subarea 3, 4 and 5

The contaminated soil is assumed to be approximately 35,000 m^3. The contaminated soil would be transported to seashore for use as fill material in the construction of seaport facilities, because the contaminated soil is polluted only by seawater. The excavated soils would be replaced with clean soils, approximately 25,000 m^3, supplied from surroundings.

(1) Content of the Excavating Work

The content of the excavating work is shown as below.

1) Location of excavating : Between DH-3 and PS-2

2) Specification of grouting work

- Length of excavating zone : 400 m
- Width of excavating zone : 10 ~ 70 m
- Depth of excavation : 0 ~ 30 m
- Total volume of excavation : 35,000 m^3
- Backfilling volume of clean soil : 25,000 m^3

3) Equipments

- Bulldozer : D-8 class with ripper : 3 units :
- Hydraulic excavator : $2m^3$ class : 3 units
- Dump truck : 20 t class : 10 units

(2) Work schedule

The work schedule of the excavating work is shown in Table 13.4. The construction period is about 4 months.

Table 13.4 Work schedule of the Excavating Work

Work items (month)	1	2	3	4	5	Remarks
1. Preparation, mobilization						
2. Excavation						
3. Transportation						
4. Backfilling						Clean soil
5. Demobilization						

(3) Cost Estimation

Total cost for the excavating work at Subarea 3 is estimated US$ 1,100,000, shown as below.

1)	Excavation-Transportation cost	US$	800,000
	・Excavation cost		300,000
	・Transportation cost		500,000
2)	Replacing cost	US$	300,000
	Total	US$	1,100,000

(Cost includes overhead expense, contingencies and miscellaneous expenses.)

13.2.3 Countermeasures in Subarea 4 (Alternatives-5A and 5B)

Subarea 4 consists of 3.5 km of the main channel of Wadi Suq from drill hole DH-3 to drill hole DH-4 near KM14 at the small village of Sagha (Figure 13.6). No sources of groundwater pollution were identified within this subarea. However, groundwater in Subarea 4 is contaminated with salt and heavy metals resulting from transport of contaminated groundwater from upstream sources. A natural constriction in the wadi channel occurs at KM14. This natural constriction provides an excellent opportunity to intercept the subsurface flow either through a cutoff trench or a system of extraction wells (Figure 13.6). Intercepting groundwater at KM14 provides an opportunity to treat or dispose of the water for the purpose of reducing the salt loadings at down gradient locations.

In case without any contamination countermeasures at KM14, the contaminated groundwater including salinity and heavy metals will continue to flow down along Wadi Suq and reach to Falaj al Qabail and Sohar agricultural and residential area as well as extending the damage by the contaminated groundwater. Therefore, it is necessary to implement effective countermeasures as soon as possible.

Tributary No.1 joins with mainstream of Wadi Suq at KM14 (Subarea 4). Although the groundwater along main stream of Wadi Suq is contaminated, the groundwater along Tributary No.1 is clean. Therefore, the location of contamination countermeasures at KM14 would be installed in the vicinity of DH-4 upstream of the confluence with Tributary No.1 shown as Figure 13.6.

The countermeasure alternatives in the Subarea 4 consist of two alternatives, namely Alternative-5A and Alternative-5B.

- Alternative-5A : Pumping by wells and water conveying
- Alternative-5B : Pumping by trench and water conveying

(1) Alternative-5A

Alternative-5A of the Subarea 4 is planning to extract the contaminated groundwater by aligned pumping wells (Figure 13.6). The content of the alternative is described as below.

- A line of appropriately spaced groundwater extraction wells would be installed perpendicular to the flow direction in the vicinity of Drill Hole DH-4.
- This system of wells would capture saline groundwater upstream of the confluence of Wadi Suq and Tributary-1 in order to allow the relatively clean water from the tributary to continue to recharge the wadi aquifer down gradient of KM14.
- The pumped contaminated groundwater will be conveyed to the water treatment plant.

a. Content of the Pumping Well Work

The content of the pumping well work is shown as below.

1) Location of pumping wells : DH-4
2) Specification of pumping well work
   - Width of pumping wells zone : 460 m
   - Number of pumping well : 22 wells (20m interval)
   - Diameter of pumping wells : 12~1/4 inch
   - Length of pumping wells : Average 30 m
   - Diameter of screen : 8 inch (PVC)
   - Depth of screen : 4 ~ 30 m
   - Pumping volume : 150 m^3/day
   - Calculation of pumping volume
     (Calculating formula)

$$Q = \frac{\pi k \left(H^2 - Ho^2\right)}{2.303 \log(R/Ro)} \quad \cdots\cdots\cdots\cdots \quad \text{(Deep well)}$$

Q : Pumping volume (m^3/s)
k : Permeability coefficient (m/s)
H : Water head (m)
Ho: Depth of groundwater table (m)
R : Radius of influence (m)

$$R = 3000 \cdot Sw \cdot k^{1/2}$$

$$3000 \cdot 11.39 \cdot (7.76 \times 10^{-6})^{1/2} = 95.2 \text{ m}$$

Ro: Radius of water well (m)

$$= \frac{3.14 \times 7.76\times10^{-6} \times (6.39^2 - 0^2)}{2.303 \log (95.2/0.203)}$$

$= 1.62 \times 10^{-4}\ m^3/sec$

$= 13.9\ m^3/d/well$ (Total pumping volume : 308 m^3/day)

- Pumping volume : 150 m^3/day

3) Equipments

- Percussion drilling rig : Air-form : 1 unit
- Pump : 22 units
- Water gauge : 22 units

b. Work schedule

The work schedule of the pumping work is shown in Table 13.5. The construction period is about 4 months.

Table 13.5 Work schedule of the Pumping Work

Work items (month)	1	2	3	4	5	Remarks
1. Preparation, mobilization	—					
2. Drilling work	——	——	—			Gas-pipeline Seawater pipeline
3. Cleaning, installation of pump		——	——			
4. Subsidiary work			—	——		
5. Demobilization				—		

c. Cost Estimation

Total cost for installing the pumping system in Subarea 4 is estimated US$ 800,000, shown as below.

1) Pumping well work cost	US$		500,000
・Boring cost			300,000
・Cleaning, etc. cost			40,000
・Fee of pumps			160,000
2) Replacing cost		US$	300,000
Total		US$	800,000

(Cost includes overhead expense, contingencies and miscellaneous expenses.)

(2) Alternative-5B

Alternative-5B of the Subarea 4 is planning to extract the contaminated groundwater by cutoff trench and pumping contaminated groundwater (Figure 13.6). The content of the alternative is described as below.

- A line of appropriately spaced groundwater extraction wells would be installed perpendicular to the flow direction in the vicinity of Drill Hole DH-4.
- The conceptual design of the proposed cutoff trench is illustrated in Figure 13.7.
- The depth of bedrock at the cutoff trench ranges from 5m to 14m. The bedrock consists of weathered to strongly weathered basaltic pillow and massive lavas. The Wadi sediments mainly consist of consolidated diluvial deposits by calcrete and loose alluvial deposits in ascending order.
- Cutoff wall will be installed at the downstream side of the trench.
- Weathered and fracture developed bedrocks will be improved rock quality by curtain grout.
- During construction of the cutoff trench, measures would be taken to protect the natural gas pipeline and seawater pipeline buried in the Wadi sediments. Also, the highway would have to be temporarily rerouted during construction.
- This system of wells would capture saline groundwater upstream of the confluence of Wadi Suq and Tributary 1 in order to allow the relatively clean water from the tributary to continue to recharge the wadi aquifer down gradient of KM-14.
- The pumped contaminated groundwater will be conveyed to the water treatment plant.

a. Content of the Cutoff Trench Work

The content of the cutoff trench work is shown as below.

1) Location of cutoff trench : DH-4

2) Specification of cutoff trench work
   - Length of cutoff trench : 460 m
   - Width of cutoff trench : 10 ~ 15 m
   - Width of bottom of cutoff trench : 5 m
   - Excavating and replacing volume : 50,000 m^3
   - Area of bottom of cutoff trench : 5,900 m^2
   - Concrete volume of bottom of cutoff trench : 1,400 m^3
   - Concrete volume for cutoff wall at downstream side : 4,350 m^3
   - Length of joint at downstream side : 300 m
   - Cutoff wall made by membrane at downstream side : 8,500 m^2

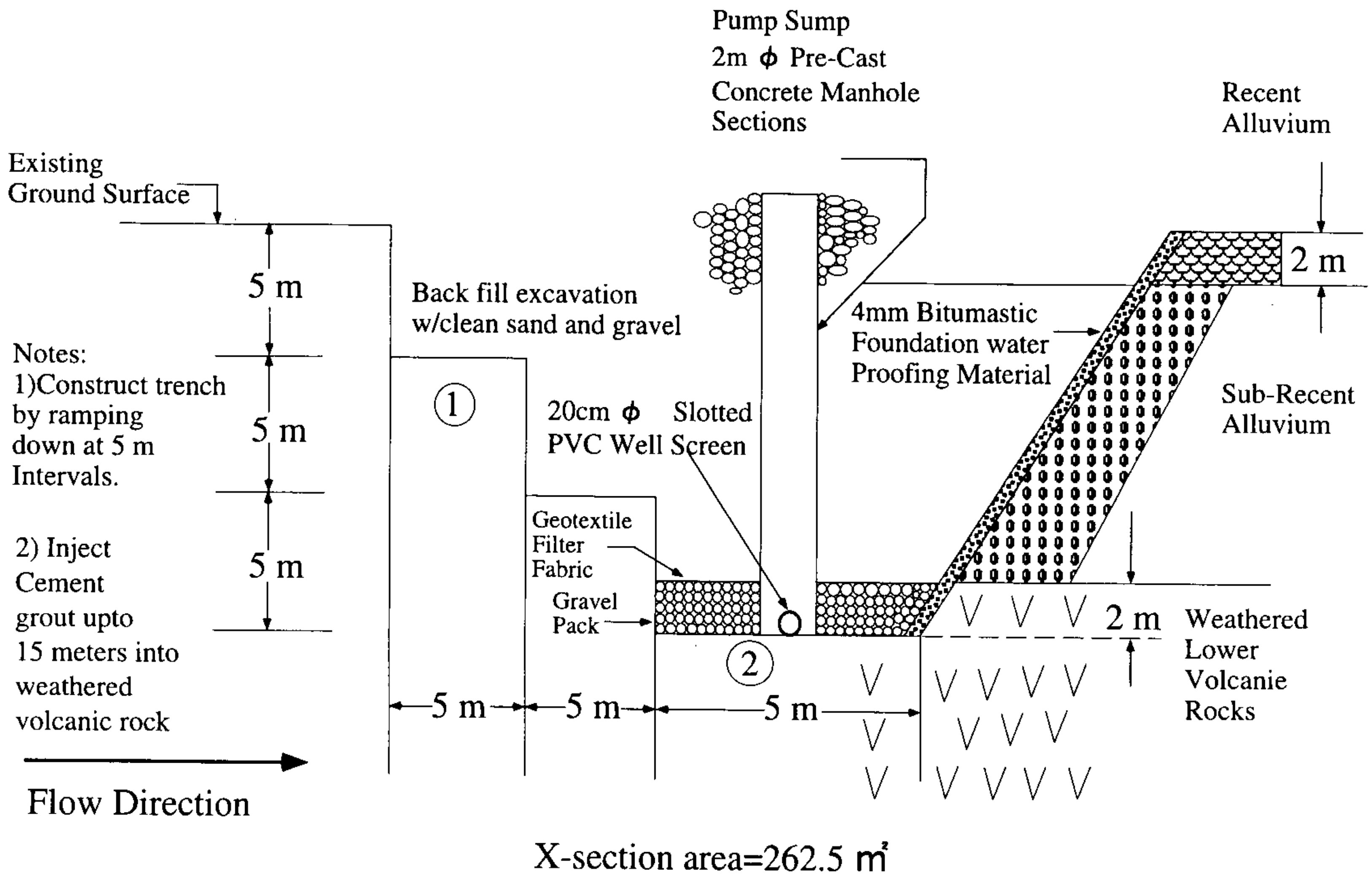


Figure 13.7 Subarea 4, Cutoff Trench Conceptional Design

- Drainage system : 1 unit
- Well made by concrete : 1 unit (Diameter : 1 m)

(Calculating formula)

$$Q = \frac{\pi k\ (H^2 - Ho^2)}{2.303 \log(R/Ro)} \quad \cdots\cdots\cdots\cdots \quad \text{(Deep well)}$$

Q : Pumping volume (m^3/s)
k : Permeability coefficient (m/s)
H : Water head (m)
Ho: Depth of groundwater table (m)
R : Radius of influence (m)

$$R = 3000 \cdot Sw \cdot k^{1/2}$$

$$3000 \cdot 6.39 \cdot (7.76 \times 10^{-6})^{1/2} = 53.4 \text{ m}$$

Ro: Radius of water well (m)

$$= \frac{3.14 \text{ x } 7.76 \times 10^{-6} \text{ x } (6.39^2 - 0^2)}{2.303 \log (53.4/31.8)}$$

$= 1.92 \text{ X } 10^{-3}\ m^3/sec$ (Total pumping volume : 165 m^3/day)

・Pumping volume : 150 m^3/day
・Others : Temporary construction and replacement of road, electric line, gas pipeline, etc.

3) Equipments

- Bulldozer	: D-8 class with ripper	: 2 units
- Hydraulic excavator	: 2 m^3 class	: 4 units
- Dump truck	: 10 t class	: 5 units
- Pump (for construction)	: 5 units	
- Pump (for operation)	: 1 unit	
- Water gauge	: 3 units	
- Others		

b. Work schedule

The work schedule of the cutoff trench work is shown in Table 13.6. The construction period is about 11 months.

Table 13.6　Work schedule of the Cutoff Trench Work

Work items　(month)	1	2	3	4	5	6	7	8	9	10	11
1. Preparation, mobilization											
2. Drilling survey											
3. Installation of drainage system											
4. Excavation work											
5. Concrete placing at bottom											
6. Grouting work											
7. . Concrete placing at side											
8. Backfilling work											
9. Demobilization											

c. Cost Estimation

Total cost for the cutoff trenchwork at Subarea 4 is estimated US$ 5,400,000, shown as below.

1)	Cutoff trench work cost	US$	3,500,000
2)	Drilling survey cost	US$	500,000
3)	Curtain grouting cost	US$	1,400,000
	合計	US$	5,400,000

（Cost includes overhead expense, contingencies and miscellaneous expenses.）

13.2.4 Countermeasures in Subarea 5

Subarea 5 consists of 4.0 km of the main wadi channel from KM14 at the village of Sagha to Drill Hole DH-5 (Figure 13.5). This subarea includes the village of Misial A'Sidr. Groundwater in the main channel of Wadi Suq is contaminated with salt from upstream sources throughout Subarea 5. However, relatively fresh water exists along the periphery of Subarea 5. Also, relatively clean groundwater is found in Tributary 3 which runs parallel Subarea 5 on its northern periphery.

The contaminated groundwater from Subarea 4 flows down through topographical narrow valley to the Sabarea 5. Although most of the contaminated groundwater flowed into the Subarea 5 is thought to stay in the Subarea 5, the contaminated groundwater in Subarea 5 including salinity and heavy metals will continue to flow down along Wadi Suq and reach to Falaj al Qabail and Sohar agricultural and residential areas, if no countermeasures are implemented in Subarea 5.
Therefore, it is necessary to implement effective countermeasures at Subarea 5. However, these countermeasures will be terminated when the groundwater quality at Subarea 5 improves.

The specific actions proposed under Subarea 5 are described, as follows:

- A line of extraction wells similar to that in Subarea 4 would be installed parallel to the flow direction at the approximate midpoint of Subarea 5. The extraction system would be installed between the main highway and the natural gas pipeline, as illustrated in Figure 13.5.
- It is estimated that the line sink at this location would consist of 20 wells, average 40 m deep, in a line approximately 600 m in length along the wadi. For estimation purposes, it is assumed that the groundwater extraction rate will be approximately 200 m^3/d.
- The purpose of the groundwater extraction system would be to create a line sink to remove the potential source of pollution, and it is assumed that mitigating the highly saline water in the main channel will reduce the salt and dissolved solids loads that may be affecting the water quality at Misial A' Sidr and Tributary-3.
- Contaminated groundwater extracted from the extraction wells is pumped to the water treatment plant located in Subarea 5.

a. Content of the Pumping Well Work

The content of the pumping well work is shown as below.

1) Location of pumping wells : Upstream side of DH-5
2) Specification of pumping well work
   - Width of pumping wells zone : 600 m
   - Number of pumping well : 20 wells (30 m interval)
   - Diameter of pumping wells : 12-1/4 inch
   - Length of pumping wells : 40 m
   - Diameter of screen : 8 inch (PVC)
   - Depth of screen : 20 ~ 40 m
   - Calculation of pumping volume

(Calculating formula)

$$Q = \frac{\pi k \left(H^2 - Ho^2\right)}{2.303 \log(R/Ro)} \quad \cdots\cdots\cdots\cdots \text{(Deep well)}$$

Q : Pumping volume (m^3/s)

k : Permeability coefficient (m/s)

H : Water head (m)

Ho: Depth of groundwater table (m)

R : Radius of influence (m)

$$R = 3000 \cdot Sw \cdot k^{1/2}$$

$$3000 \cdot 20.1 \cdot (7.42 \times 10^{-7})^{1/2} = 163.2 \text{ m}$$

Ro: Radius of water well (m)

$$= \frac{3.14 \times 7.42 \times 10^{-7} \times (20.1^2 - 0^2)}{2.303 \log(163.2/0.203)}$$

$= 1.41 \times 10^{-4}$ m^3/sec

$=$ 12.2 m^3/d/well (Total pumping volume : 244 m^3/day)

- Pumping volume : 200 m^3/day

3) Equipments

- Percussion drilling rig : Air-form : 1 unit
- Pump : 20 units
- Water gauge : 20 units

b. Work schedule

The work schedule of the pumping work is shown in Table 13.7. The construction period is about 4 months.

Table 13.7 Work schedule of the Pumping Work

Work items (month)	1	2	3	4	Remarks
1. Preparation, mobilization	▬				
2. Drilling work	▬	▬			Gas-pipeline Seawater pipeline
3. Cleaning, installation of pump	▬	▬	▬		
4. Subsidiary work			▬	▬	
5. Demobilization				▬	

c. Cost Estimation

Total cost for the pumping work at the Subarea 5 is estimated US$ 600,000, shown as below.

1)	Pumping well work cost	US$	500,000
	・Boring cost		340,000
	・Cleaning, etc. cost		60,000
	・Fee of pumps		100,000
2)	Pipe fittering cost	US$	100,000
	Total	US$	600,000

（Cost includes overhead expense, contingencies and miscellaneous expenses.）

13.2.5 Water Treatment Countermeasures for Contaminated Groundwater

The total pumping volume of the contaminated groundwater extracted from the Subarea 4 and 5 is estimated at 150 to 350 m^3/day, and pumped groundwater containing high salt and heavy metals should be treated water quality before discharge. It is impossible to dispose directly to the sea because of containing noxious heavy metals.

The countermeasure alternatives for the water treatment consist of two alternatives, namely Alternative-7A and Alternative-7B.

- Alternative-7A : Extraction by reverse osmosis (RO)
- Alternative-7B : Treatment totally by evaporation pond

Other technologies, including electrodialysis, ion exchange, and distillation are capable of removing anions, but are considered impractical for treating large volumes of water. The coagulating sedimentation method using lime for extracting heavy metals is not a suitable method for the contaminated groundwater, as indicated by the results of laboratory tests conducting during the site investigations. In addition, the absorption method, including tannin, etc. is too expensive for operation and is considered impractical.

(1) Alternative-7A

The contaminated groundwater extracted from the extraction sites would be pumped to a treatment system designed to remove the salt and heavy metals. The treatment system would use a membrane separation technology known as reverse osmosis (RO). RO is the only water treatment technology capable of effectively removing anions, such as chloride and sulfate from water.

A schematic process flow diagram for the proposed RO treatment plant is presented in Figure 13.8. Based on conceptual design data, the RO treatment system would produce a permeate stream of relatively fresh water of 75 to 175 m^3/day, and the permeate stream would exhibit low salt and dissolved solids levels that would be suitable for domestic or agricultural uses. The extraction rate of each ion is shown in Table 13.8.

Table 13.8 Treatment Efficiency

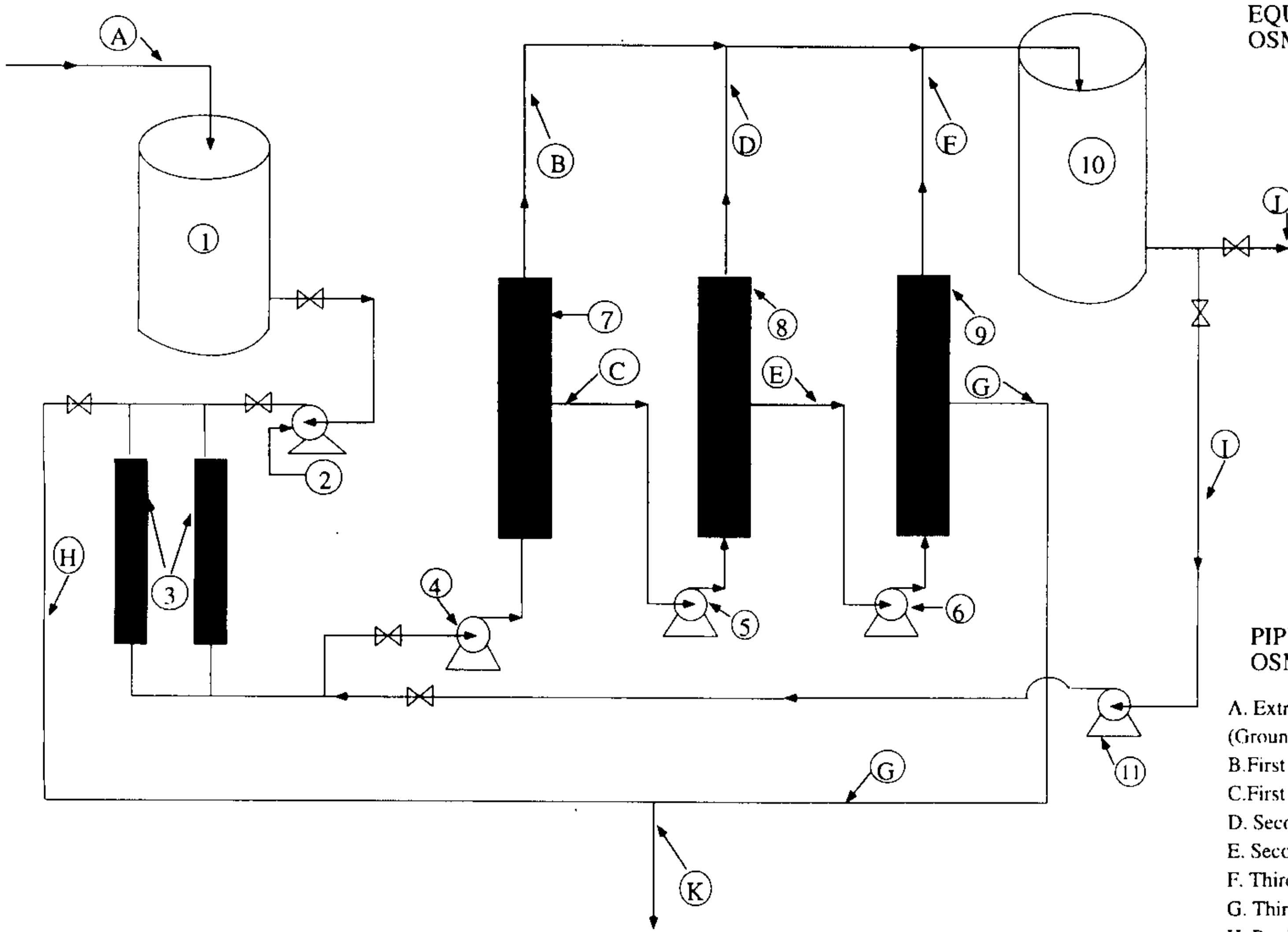
Parameters	Existing Concentration (mg/L)	Target concentration (mg/L)	Maximum allowable (mg/L)	RO treated Water quality (mg/L)	Treatment Efficiency (%)
Ca	813	200	500	35	95.7
Mg	811	200	500	35	95.7
Na	2,384	200	400	335	85.9
K	95	NA	NA	15	84.2
Fe*	0.272	0.3	1.0	0.01	96.3
Mn	0.18	0.1	0.5	0.01	94.4
As*	0.008	NA	0.01	0.003	62.5
Cu*	0.062	1.0	1.5	0.01	83.9
Cr*	0.21	NA	0.05	0.01	95.2
Pb*	0.3	NA	0.01	0.01	96.7
Ni*	0.033	NA	0.02	0.01	69.7
Zn*	0.082	3.0	5	0.01	87.8
SiO_2	100	NA	NA	10	90.0
HCO_3	167	NA	NA	25	85.0
Cl*	6,388	250	600	600	90.6
SO_4	584	250	400	30	94.9
NO_3	12	NA	50	5.0	58.3
F	0.5	NA	1.5	0.05	90.0
pH	7.15	6.5-8.0	9	6.5-7.0	NA
TDS	11,500	800	1,500	1,000	91.3

Notes : 1. Target concentrations are the same as Oman's best level of quality for drinking water to be achieved (Final Draft Omani Drinking Water Standard, 8/1998).

2. Maximum allowable concentrations are acceptable for use as drinking water if no other source is available (Final Draft Omani Standard, 8/1998).

3. RO treated water quality is predicted based on modeling results from HS Process Technologies in Denver, Colorado.

* = Data from JICA Feasibility Study from Drill Hole DH-4S. All other value are from KM-14 presented in the 1995 Ministry of Water Resources Report.



EQUIPMENT LIST FOR OSMOSIS TREATMENT SYSTEM

1. Raw Water Storage Tank
2. Pre-Filter Feed Pump
3. Dual Media Pre-Filters
4. First Stage High Pressure Stainless Steel Feed Pump
5. Second Stage High Pressure Stainless Steel Feed Pump
6. Third Stage High Pressure Stainless Steel Feed Pump
7. First Stage Reverse Osmosis Membrane Unit
8. Second Stagde Reverse Osmosis Membrane Unit
9. Third Stage Reverse Osmosis Membrane Unit
10. Permeate(Treated Water) Storage Tank
11. Pre-Filter Backwash Pump

PIPING LIST FOR REVERSE OSMOSIS TREATMENT SYSTEM

A. Extraction System Discharge Piping (Groundwater from Extraction Wells or Trench)
B. First Stage Permeate Discharge Line
C. First Stage Concentrate Discharge Line
D. Second Stage Permeate Discharge Line
E. Second Stage Concentrate Discharge Line
F. Third Stage Permeate Discharge Line
G. Third Stage Concentrate Discharge Line
H. Pre-Filter Backwash Discharge Line
I. Pre-Filter Backwash Feed Line
J. Treated Water Distribution Line

Figure 13.8 Process Flow Design for Reverse Osmosis Treatment System

The permeate stream would either be re-injected into the wadi gravels downstream of KM-14 or provided to local residents for domestic or agricultural purposes.

After water treatment, rejected water of approximately 75 to 175 m^3/day containing high salt and heavy metals will be produced . The rejected water will be will sent to the evaporation ponds and evaporated there. Two evaporation ponds are located in the Subarea 5, and the ponds will be used alternatively for managing the treatment of residues.

The evaporated residue will be finally packed by plastic bags and stored at a disposal warehouse for the protection against the scattering and re-melting by weather. The warehouse is located on the hill without any damage by temporary current of the wadi, shown in Figure 13.6. Total Cl volume of removal by the water treatment system is estimated at 921 to 2,148 kg/day.

Table 5 summarizes the initial water quality of Wadi Suq groundwater at KM-14 and the water quality after treatment. The initial load reduction resulting from the removal of salt contaminated water under this alternative is estimated at 3,970 kg per day of chloride removed.

a. Content of Water Treatment System

The content of the water treatment system is shown as below.

1) Location of water treatment system	: Subarea 5
2) Specification of water treatment system	
- Volume of treatment water	: 150 to 350 m^3/day
- Flow of water treatment plant	: See Figure 13.8
- Area of facility	: 0.5 ha
3) Specification of evaporation ponds	
- Volume of treatment water	: 75 to 175 m^3/day
- Numbert of ponds	: 2 units
- Size of ponds	: 100 m x 100 m x 2 sites
- Area of ponds	: 10,000 m^2 x 2 sites
- Depth of ponds	: 1 m (Height of embankment:1m) : Total 2m
- Volume of evaporation	: 15,000 m^3 x 2 sites
- Sealing materials	: Double HDPE membrane
- Weight of residue	: 1.6 to 3.7 t/day
4) Drainage system	
- Location of drainage	: Re-injection at downstream of the water treatment plant
5) Disposal warehouse	

- Weight of residue : 590 to 1,350 t/year ≒ 400 to 900 m^3/year
- Volume of residue : 4,000 to 9,000 m^3 (after 0 ~ 10 years)
  2,000 to 4,500 m^3 (after 10 ~ 20 years)
  1,000 to 2,250 m^3 (after 20 ~ 30 years)
- Size of facility : 40 m x 50 m x 5 m (height) x 1 to 2 units
  Volume : 10,000 m^3/unit

b. Work Schedule

The work schedule of the water treatment facility construction work is shown in Table 13.9. The construction period is about 9 months.

Table 13.9 Work schedule of the Water Treatment Facility Construction Work

Work items (month)	1	2	3	4	5	6	7	8	9	Remarks
1. Preparation, mobilization	—									
2. Construction work of facilities	—	—	—	—	—	—	—			
3. Installation of RO and others				—	—	—				
4. Subsidiary work				—	—	—				
5. Testing of treatment							—	—	—	
6. Construction of evaporation pond		—	—	—	—	—	—			
7. Construction of drainage system				—	—	—				
8. Construction of warehouse		—	—	—	—	—	—			
9. Demobilization									—	

c. Cost Estimation

The cost for the water treatment plant construction work is estimated at US$ 1,000,000 to 1,500,000 shown as below, that of the evaporation ponds is US$ 400,000 to 700,000, and that of the warehouse is US$ 300,000 to 900,000. Total cost is estimated at US$ 1,700 to 3,100,000.

1)	water treatment plant construction work cost	US$	1,000,000 - 1,500,000
	- RO cost		400,000 - 800,000
	- House construction cost		300,000 - 400,000
	・Fee of test, etc.		300,000 - 300,000
2)	evaporation ponds construction cost	US$	400,000 - 700,000
	・Earth work cost		170,000 - 300,000
	・HDPE covering cost		200,000 - 350,000
	・Fence, etc.		30,000 - 50,000
2)	Warehouse construction cost	US$	300,000 - 900,000
	・Construction cost		300,000 - 900,000
	Total	US$	1,700,000 - 3,100,000

（Cost includes overhead expense, contingencies and miscellaneous expenses.）

(2) Alternative-7B

The Alternative-7B is treated all of pumped contaminated groundwater at the evaporation ponds. Total volume of treatment is same as 150 to 350 m^3/day, but no water treatment is performed. Therefore, the groundwater level will be drawn down.

The pumped contaminated groundwater will be sent to the evaporation ponds and evaporated, instead of being treated by RO. Two evaporation ponds are located in Subarea 5, and the ponds will be used alternatively for the treatment of residues.

The evaporated residue will be finally packed by plastic bags and stored at disposal warehouse for the protection against the scattering and re-melting by weather. The warehouse is located on the hill without any damage by temporary current of the wadi, shown in Figure 13.6. Total Cl volume of removal by the water treatment system is estimated at 958 to 2,236 kg/day.

a. Content of Water Treatment

The content of the water treatment by the evaporation pond is shown as below.

1) Location of water treatment : Subarea 5

2) Specification of evaporation ponds

- Volume of treatment water : 150 to 350 m^3/day
- Numbert of ponds : 2 units
- Size of ponds : 100 m x 100 m x 2 sites
- Area of ponds : 10,000 m^2 x 2 sites
- Depth of ponds : 1 m (Height of embankment:1m) : Total 2m
- Volume of evaporation : 15,000 m^3 x 2 sites

- Sealing materials : Double HDPE membrane
- Weight of residue : 1.8 to 4.1 t/day

3) Disposal warehouse
- Weight of residue : 660 to 1,500 t/year ≒ 440 to 1,000 m^3/year
- Volume of residue : 4,400 to 10,000 m^3 (after 0 – 10 years)
  2,200 to 5,000 m^3 (after 10 – 20 years)
  1,100 to 2,500 m^3 (after 20 – 30 years)
- Size of facility : 40 m x 50 m x 5 m (height) x 1 to 2 units
  Volume : 10,000 m^3/unit

b. Work Schedule

The work schedule of the evaporation pond, etc. construction work is shown in Table 13.10. The construction period is about 8 months.

Table 13.10 Work schedule of the Evaporation Pond, etc. Construction Work

Work items (month)	1	2	3	4	5	6	7	8	Remarks
1. Preparation, mobilization	—								
2. Construction of evaporation pond	—	—	—	—	—	—	—	—	
3. Construction of warehouse	—	—	—	—	—	—	—	—	
4. Demobilization								—	

c. Cost Estimation

Total cost for the evaporation ponds, etc. construction work is estimated US$ 700,000, shown as below.

1)	evaporation ponds construction cost	US$	400,000
	・Earth work cost		170,000
	・HDPE covering cost		200,000
	・Fence, etc.		30,000
2)	Warehouse construction cost	US$	300,000
	・Construction cost		300,000
	Total	US$	700,000

(Cost includes overhead expense, contingencies and miscellaneous expenses.)