SUBSURFACE REMOVAL OF IRON AND MANGANESE FROM GROUNDWATER – CASE STUDY

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ABSTRACT

Although subsurface removal of iron and manganese from groundwater had been used in Europe for decades, it doesn't have an established design criteria and its application depends on the field practice and trials. The first application of the method in Egypt was performed few years ago by a pioneer water company. A full technical and economical study was carried out to evaluate the capabilities of the method and the operation performance of plants using this method. Technical evaluation included deferent parameters such as; capability of iron and manganese removal, other elements removal, starting-up period, effect on the groundwater microbiology, wells draw down level, method complexity and reliability, chemical requirement, wasted water, method compatibility and effect of stoping and restarting of the wells. Economically, the method evaluated in comparison with other method used for the same purpose. In general, the method obtained good results in the removing iron and manganese with long operation cycle of yield equal to 10. Production cost of one cubic meter of water by using the method is a little bit higher than the case of water supply from wells without any removing of iron and manganese, It fluctuates between 11.0 and 12.1 (Egyptian piaster) according to the estimated lifetime of the well, and is less than 50% of the production cost of water using the other alternatives.

Key Words: Groundwater – Iron – Manganese – Subsurface removal – Under ground removal.

INTRODUCTION

Groundwater is generally considered as the best source for potable water as it is well protected from contamination. The most common problem limiting the use of groundwater in Egypt is its high iron and/or manganese content. This problem is often overcome by applying treatment before use. Different techniques to remove iron and manganese are in use now, but the search for better, cheaper and safer technique will never stop. Iron and manganese in waters are not considered as health hazards but mainly as esthetical and technical problems. The world health organization stipulates that the maximum acceptable level of iron in drinking water is less than 0.3 mg/l and manganese less than 0.1 mg/l. The Egyptian authorities limit the iron in drinking water to 1.0 mg/l and manganese to 0.5 mg/l. Iron and manganese in water in excess of the above levels have no direct effect on health, but are objectionable primarily because the precipitation of iron alters the appearance of water, giving it a turbid yellow-brown to black. In addition, the deposition of iron precipitates causes damage to plumbing fixtures and laundry.

In the Delta many wells containing iron and manganese are polluted by non-point sources of pollution such as sewage contamination and old decomposed substances of organic and plant origin. Pollutants may contain organic carbon, ammonia, nitrite and nitrate. Aeration in many cases is not enough to oxidize iron and manganese in complex forms with organics. Most of the treatment plants use potassium permanganate as an oxidizer and alum as a coagulant followed by pressurized closed sand filters. Such plants need high-trained labor and continuous monitoring of the doses of chemicals.

In situ iron and manganese removal has proven to be available technique for diminishing the iron and manganese concentrations in groundwater. The technique involves a cyclic injection of oxygenated water into the aquifer, and withdrawal of injected water and groundwater in which iron and manganese concentrations are lower than in the native groundwater. This method is applied in a number of European countries successfully under different names [1-4].

Iron precipitates can be quite massive and often cause serious clogging of drinking water wells. However, clogging has not been reported for in situ iron removal, even though systems have been operating for more than 20 years [7]. The lack of clogging suggests that, precipitation of iron takes place at some distance away from the well, and possibly at varying locations in time.

Seyfried and Olthoff, [8] presented an introduction to the historical development of underground removal of iron and manganese from groundwater and a survey of underground removal plants currently in operation worldwide. The engineering process of underground groundwater treatment and those treatment mechanisms viewed effective by the authors are described. The aquifer serves as a natural treatment area in the underground removal of iron and manganese. By introduction of oxygenated water, a treatment area is created in the aquifer, in which iron and manganese are removed from the groundwater by adsorption and oxidation. An underground treatment plant consists of at least two wells with additional feed wells if necessary whereby each well is operated in temporal alternation as both feed and withdrawal well. The underground treatment at one well is divided into three phases:

- Oxygen feed,
- Rest phase (crystallization phase),
- Withdrawal (adsorption phase).

In the feed phase, the oxidant, usually atmospheric oxygen, is transported into the treatment area dissolved in feed water and oxidizes the iron and manganese retained in the preceding withdrawal phase.

The rest phase allows completion of oxidative processes and development of crystalline iron and manganese oxide hydrates.

In the withdrawal phase, at the start of withdrawal, groundwater containing iron and manganese reaches the treatment area. Iron (II) and manganese (II) ions are adsorbed by the iron (III) oxide hydrate in exchange for H+ and metal cations (primarily Ca2+) which are bound less tightly. The amount of iron and manganese-free groundwater that can be withdrawn with use of atmospheric oxygen and continuous withdrawal is 3 to10 times that of the feed water amount, depending on aquifer characteristics and iron and manganese content of the groundwater. The iron (II) and Mn(II) concentrations increases in withdrawal water. Upon or before reaching the threshold value for Fe and Mn in the drinking water, the withdrawal is normally closed. Oxidation process does not take place during the adsorption phase.

The gross chemical mechanism of in situ oxidation appears to be simple, in that a given amount of oxidant is injected, and is consumed by reduced substances in the aquifer. Several theories have been advanced on in situ iron and manganese removal, and specifically, how the electron acceptor in injection water contacts dissolved $Fe^{2+}$and Mn^{2+} in groundwater. Rott and Lamberth, [4] suggested that, bacteria play a decisive role in the process. The repeated injection of oxygenated water and withdrawal of reduced groundwater supplies nutrients and creates favorable growth conditions for microorganisms. Increase of efficiency with successive runs was related to growth of the bacterial community. This theory implies that the microorganisms are able to take away and store the oxidant, and to use it again when flow is inverted and the iron-containing groundwater flows by. It requires changes in the oxidation state of organic matter, and organic matter reactions must be invoked to capture a considerable part of the oxidant. Rott et al. [5] hypothesized that, sorption of oxygen on aquifer sediment occurred and enabled contact with dissolved iron. The oxygen would be released when iron-containing groundwater passed the sorption sites when flow is reversed. The theory may produce results that are indiscernible from oxidation of sorbed Fe^{2+}. However, sorption of oxygen on aquifer sediment is not well documented, and this theory has not been considered.

Van Beek and Vaessen, [6] were the first to propose that Fe^{2+}, sorbed on iron-oxyhydroxide in the aquifer, may become oxidized by the injected oxidant. The resulting Fe^{3+} precipitates and forms a new layer on the existing iron-oxyhydroxide, which is able to sorb Fe^{2+} from groundwater when flow is reversed. Meyerhoff, [7] suggested that, the cation exchange capacity of the sediment (which includes clay minerals and other exchangers besides iron-oxyhydroxide) is also available for exchange of Fe^{2+}. The increase in efficiency was related by Van Beek and Vaessen [6] to the initial consumption of oxidant by other reductants than Fe^{2+} and to the increase of iron-oxyhydroxide during successive cycles.

Egyptian Experience

El-Beheira Water Company (BWC) has signed an agreement with Netherlands Management Cooperation Program (NMCP) and Amsterdam Water Supply (AWS) in the field of iron and manganese removal from groundwater. Whereas Beheira Water and Wastewater Company is the responsible entity for supplying the Governorate with potable water, the south part of the Governorate depends extensively on groundwater; and whereas many wells had been closed due to iron and manganese problems, the company has re-developed the wells through maintenance process and studying the best methods for iron and manganese removal. The company has cooperated with the Dutch side in studying groundwater in different places in the Governorate and studying the different alternatives for iron and manganese removal. The work team succeeded to modify sub-surface method applied in some other countries. It is called Beheira Underground Removal of Manganese (BURMAN) process.

The method was applied in many sites in El-Beheira Governorate. The detailed evaluation process included 5 wells located in two plants and there main characteristics are as follow;

Table 1: Subsurface iron and manganese removal wells characteristics

Well name	Well data			Pump discharge, m^3/h
	Diameter, mm	Total depth, m	Screens length, m	
Kom Hamada (3)	150	48.5	30	20
Itay El-Baroud (1)	250	60	12	120
Itay El-Baroud (2)	250	60	12	80
Itay El-Baroud (4)	250	93	40	80
Itay El-Baroud (5)	250	93	40	80

The applied method for removing iron and manganese consisted of three stages:

1- Injection: efficiently aerated water is injected into the selected well. The quantity of water is determined according to the design of the well and the practical needs on site.
2- Rest: where the injection is stopped and the well is left for a while without abstracting water from it.

3. Abstraction: the well is operated and abstracted water is pumped to served areas until reaching the maximum permissible limit of iron and manganese, and then a new cycle is repeated.

EVALUATION METHODOLOGY

The Egyptian experiment is evaluated technically and economically, the methodology used is described in next section.

Technical Evaluation

Technical evaluation of any unit operations and processes must consider a relevant group of factors. Each factor is important in its own rights, but from the past experience in the operation and maintenance problems in Egypt, the most important factors are the reliability and complexity of the method. Factors that were considered in the evaluation are as follow;

- Process performance:
    - The capability of the method for iron and manganese removal.
    - The capability of the method for other elements removal.
    - Starting-up period.
    - Effect of the method on the groundwater microbiology.
    - Pump pressure head conservation.
    - Effect on the Groundwater Draw down Level.
    - Pyrite in the subsoil.
- Complexity:
    - Complexity in studies and design.
    - Complexity in construction.
    - Complexity in operation and maintenance.
- Chemical requirement:
    - Chemicals needed for the treatment process it self, its amount and effect.
- Sludge produced:
    - The amount and constituents of the sludge produced from the process.
- Wasted water:
    - The ratio of water used through washing of process units and medias.
- Reliability:
    - The stability of effluent quality for long time.
    - The rate of sudden drop in operation.
    - The need for outsider team for maintenance.
- Compatibility
    - The Capability of the method with the existing facilities.

Economical Evaluation

For the sake of economical evaluation of the method, the cost of production of one meter of water by the subsurface method was compared with the production made by four other methods that traditionally used in small cities and communities in Egypt, whish are;

- A well with no removal of iron and manganese.
- Iron and manganese removal unit by traditional methods (chemical oxidation).
- Iron and manganese removal unit by biological method.
- Surface water treatment unit (Compact unit).

The biological method was tested in Egypt on a pilot scale basis, the costs of the unit was estimated based on assumed design and made from concrete structures. The unit consist mainly from cascade for aeration then up-flow gravel filter then sand filters.

RESULTS AND DISCUSSIONS

Technical Evaluation

Capability of the Method for Iron and Manganese Removal

The maximum iron and manganese concentrations were 0.96 mg/l and 1.35 mg/l in the eleven wells that data could be gathered. The method obtained results comply with the Egyptian and World Health Organization standards in the treated water for the eleven wells. Table 2 represents the iron and manganese concentrations in the wells before applying the method. The method was applied outside Egypt on wells produced water contains iron and manganese with concentrations 10 mg/l and 1.3 mg/l.

Table 2: Iron and manganese concentration in wells water before applying the subsurface removal

Well name	Iron concentration, mg/l	Manganese concentration, mg/l
Kom Hamada (3)	0.05	0.38
Itay El-Baroud (1)	0.38	1.00
Itay El-Baroud (2)	0.43	1.03
Itay El-Baroud (4)	0.42	0.83
Itay El-Baroud (5)	0.44	0.79
El-Sokhna	0.32	0.68
Manaia (1)	0.95	0.77
Manaia (2)	0.60	0.90
Saft El-Enab	0.96	1.35
Beban	0.96	0.81
Bream	0.27	0.11

Capability of the Method for Other Elements Removal

Although the groundwater analysis for other constituents rather than iron and manganese was limited, the available dada shows some reduction in the concentration of ammonia, sulfate, phosphate and nitrate. The removal of such substances were achieved after few days of application. Figure 2 shows the concentration before and after the applying of the subsurface method.

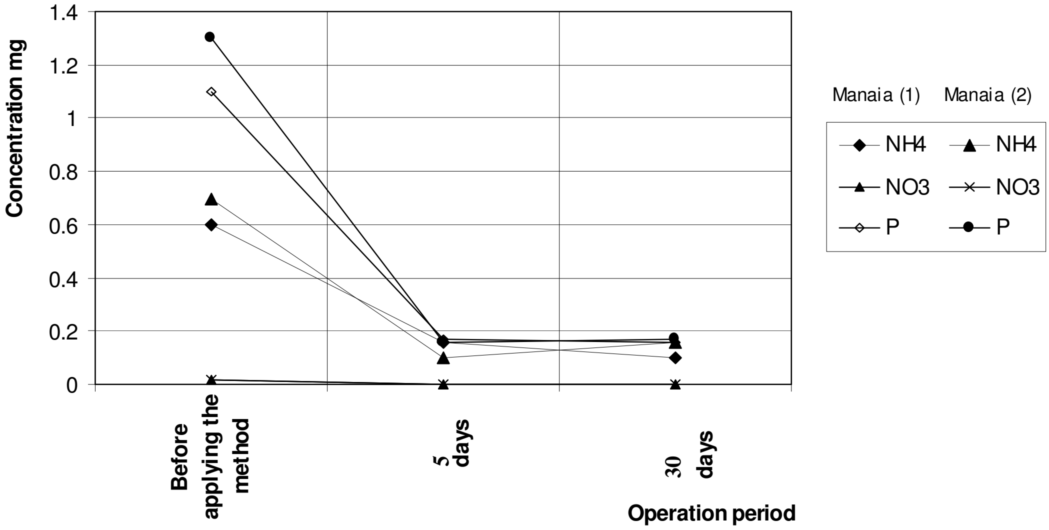

Fig 2: Concentration of some substances in the groundwater before and after applying the subsurface removal method

Starting-Up Period

The optimum operation of the method is to get the maximum volume of abstracted water with iron and manganese less than the standard in one cycle. At operating the wells for the first time with subsurface method the water continually abstracted in the abstraction phase until the iron and manganese reaches the maximum desired value, the abstracted water increased through the operation cycles until reaching the maximum value, which considered is the volume of steady operation. The number of cycles until reaching the steady operation situation was not the same for all the wells included in this study. It can be shown in figure 3, the starting-up cycles were about 19 cycles and the maximum abstracted water was 8000 m^3 for Itay El-Baroud well no (1), whereas, for Itay El-Baroud well no (5) the starting-up cycles was more that 55 cycles and the maximum abstracted water was more than 15000 m^3, weren't reached through the evaluation period.

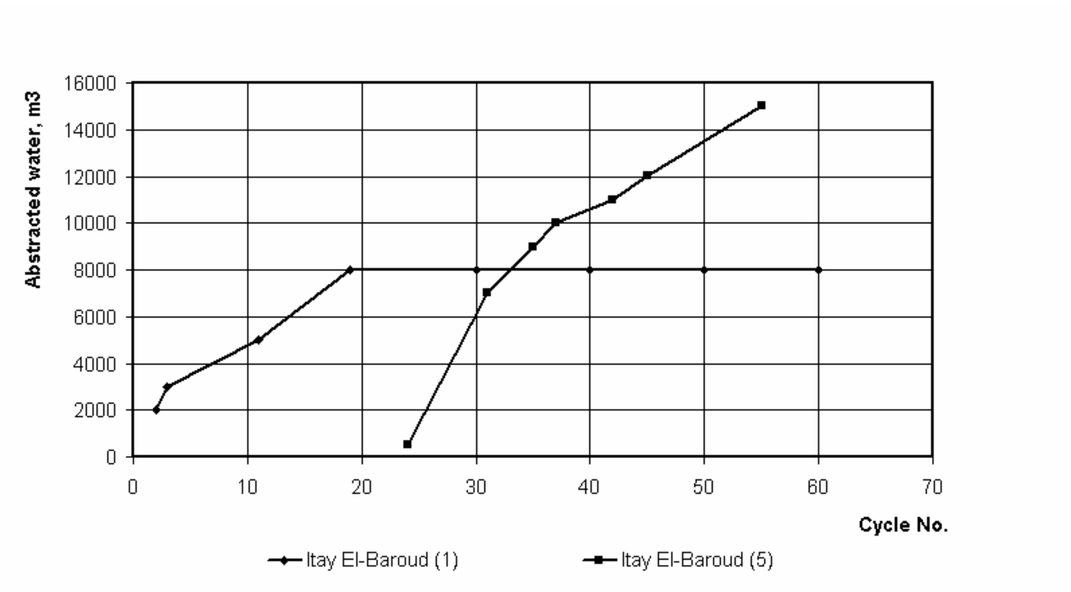

Fig 3: Starting up period of wells 1 and 2 in Itay El-Baroud plant

Effect of the Method on the Groundwater Microbiology

The groundwater is considered to be the most pure water resource regarding biological pollution. Some of the wells in the study area were found to be polluted by fecal microorganisms, source of pollution was expected to be from the bottomless septic tanks near the wells. An analysis for the fecal coliform was made for some of the wells water before and after the application of the method. Table 3 shows the results for the groundwater analysis. The method was found to have no effect on the microbiological properties of the water either positive or negative effect. The injection of aerated water to groundwater may enhance the growth of some aerobic and anoxic microorganisms such as iron bacteria, which live in the presence of iron and manganese salts, iron bacteria may have effect on the hydraulic conductivity of the soil around the wells.

Table 3: Effect of the method on the microbiological properties of groundwater wells

Well	After applying the subsurface method	Before applying the subsurface method
Itay El-Baroud (1)	-	-
Itay El-Baroud (2)	-	-
Itay El-Baroud (4)	+	+
Itay El-Baroud (5)	-	-
Manaia (1)	-	-
Manaia (2)	-	-

- No presence of fecal coliform bacteria
+ Presence of fecal coliform bacteria

Pump Pressure head Conservation

In most of groundwater plants with no treatment water discharged directly to they network using the wells pumps head. Using of treatment plant after wells needs to break the pressure and re-pump the water again to the distribution network. The subsurface removal of iron and manganese method doesn’t need excess pumps more than the wells pumps.

Effect on the Groundwater Draw down Level

The groundwater level was monitored continuously at the wells, and unexpectedly the effect on the draw down was minimal even after 18 months of operation. Figure 4 shows the draw down test on well no 4 in Itay El-Baroud after 16 months of operation. It was reported that over 3000 wells in Germany use subsurface methods were being operated twenty years with no serious clogging. The unclogging may be considered due to the alternated motion of water through abstraction and injection, which disperse the oxides through the soil in a large area around the well.

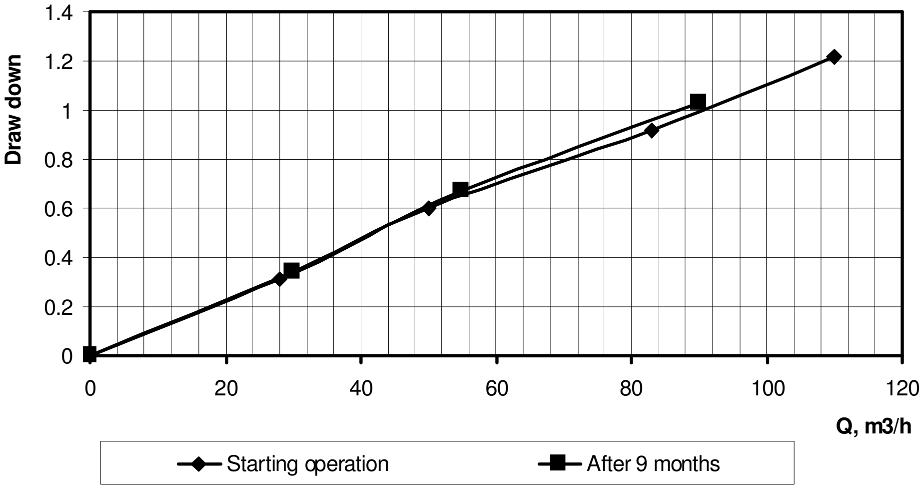

Fig 4: Draw down tests on well no (4) with interval of 16 month Itay El-Baroud plant

Pyrite in the Subsoil

Pyrite (ferrous sulphide - Fes_2) is found naturally in some soils. Its presence cause two problems for subsurface removal method; first, is the high oxygen consumption, second, ferric hydroxide formation, which effect the removal efficacy of iron and manganese, second, is the presence of some heavy metals in the pyrite crystals which are released through the dissolving of the crystals and found in the abstracted water from the well. Theoretically the release of heavy metals can’t be estimated and should be monitored through water analysis. In our case, analysis of groundwater after applying the subsurface removal method didn't show heavy metals presence. The next equation shows the reaction of oxygen with pyrite in the presence of water

$$2FeS_2 + 15O_2 + 7H_2O \text{ ------ } Fe\,(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (1)$$

Complexity

As in any water engineering project, the implementation process should go through three main phases; studies and design, construction and operation & maintenance. Regarding design, the process still doesn't have a fixed clear design criteria to be followed by designer. Although the process components are very simple, the operation parameters has to be defined by trials in the field. Construction process is not more complex than construction traditional wells. The main elements to be constructed are the wells, aeration tank, which can be a steel structure and piping system. Operation and maintenance of the method in our case were carried out with local engineers and technician, the work team learned the operation and maintenance instruction and became an independent team in short time.

Chemical Requirement

No chemicals were used in the removal of iron and manganese by subsurface method, except the chlorination of water before supplying to the consumers. The removal process is expected to be carried out underground through the adsorption of iron and manganese ions on the soil particles covered by a layer of oxides. The un-using of chemicals in the operation has its positive effect on the cost, operation safety, operation simplicity, consumer safety and environment.

Sludge Produced

As the iron and manganese removal occurs in the subsoil no oxides produced above the ground, it accumulates in some form in soil around the wells. It could be considered as an indirect disposal of sludge in ground. The aerated water used in injection phase is considered to be treated water from another well, but due to the presence of iron and manganese concentrations under the standard, very little oxides accumulate inside the aeration tank and desludged from time to time. It is considered a good advantage for the subsurface removal over traditional methods which produce large volumes of iron and manganese oxides in addition to the residual chemicals used in oxidation.

Wasted Water

Water used in water production process itself is part of the produced water and can be named as wasted water. Usually wasted water is used in filters washing, drawn water in desludging and chemicals dilution. In the subsurface removal method a certain amount of the produced water is aerated and injected in the well, and then, through abstraction phase the injected water is abstracted again as a treated water, the injected water can be considered as the wasted water. In our case the injected water in all wells was 2,000 m^3 and the abstracted water varied from one well to another, the maximum volume abstracted was 20,000 m^3, the wasted water was in minimum 10% of the produced water.

Reliability

Reliability in water production can be defined as the sustainability of production efficiency for a certain period without sudden drop and with minimal periodical maintenance. Reliability is so important in public utilities such as drinking water supply. In our case the produced water iron and manganese concentrations were almost constant at the same volumes of injected and abstracted water. Figure 5 shows that stability of manganese concentration in the produced water increased with further cycles.

The sudden drop in operation is almost the same for wells work with no treatment plants, it is expected as there no complicated equipment is included in the process in comparison to other treatment processes. That advantage is reflected on operation sustainability as the method doesn't need special experts or supplies such chemicals or green sand for operation and maintenance.

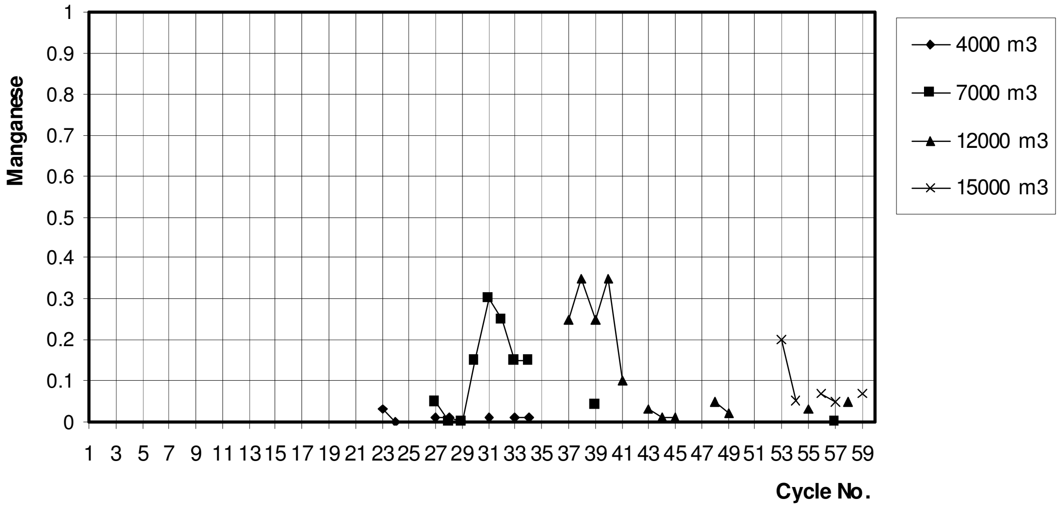

Fig 5: Manganese removal at different abstracted water in Itay El-Baroud

Compatibility

The application of the subsurface method in Egypt was found to be compatible with the following items;

- Groundwater with iron concentration ranged form 0.32 mg/l to 1.00 mg/l and manganese ranged from 0.05 mg/l to 1.03 mg/l.
- Wells with screen depth down to 100 meters and groundwater surface depth about 4 meters were suitable for the application of the method. Previous conditions are almost the same in the north delta area of Egypt. The applicability with wells in the western desert, where the well depths exceed 1000 meters and with artesian natural pressure is not clearly know.

- The method was applied in wells with surface pumps which uses suction to left water from underground, whereas, using of deep submersible pumps were not tested.
- The method was totally compatible with the local labour.

Economical Evaluation

Financial Evaluation

The cost calculations were made based on year 2000 prices using Egyptian currency (LE). It is found that the investment cost of subsurface method is lower than other proposed alternatives. It represents about 40% of the investment cost of using traditional methods to remove iron and manganese. the production cost of one cubic meter of water by using subsurface method is a little bit higher than the case of water supply without removing iron and manganese. It fluctuates between 11.0 and 12.1 piasters according to the estimated lifetime of the well, and is less than 50% of the production cost of water using the other alternatives. Table 4 shows the detailed cost breakdown for each alternative.

CONCLUSIONS

- Experience of iron and manganese removal from groundwater by subsurface method in Egypt achieved good results in improving concentration of iron and manganese in wells where experiment was applied.
- Water aeration and injection into the ground may lead to positive changes in the other chemical ingredients of drawn groundwater, and this is a subject which requires more studies to determine additional positive influences. However it's not expected to have negative influences.
- Period of operation start-up differs according to site, operation conditions, and iron and manganese concentration in groundwater before applying the approach.
- Although applying subsurface method is considered safe from bacteriological point of view, it is preferred to make continuous analysis and monitoring wells where this approach is applied.
- In spite of the limited Egyptian experience in this field which doesn't exceed few years, the application results inside and outside Egypt indicate that wells were not blocked even after long period of operation. It's necessary to make accurate monitoring for the well situation during operation.

Table 4: Detailed cost breakdown for different water treatment alternatives

Item	**Groundwater**				**Surface water**
	Biological method	**Subsurface method**	**Conventional iron and manganese removal**	**No iron and manganese removal**	**Compact unit**
1- Capital cost, LE					
Construction of 2 wells	150,000	150,000	150,000	150,000	
Civil works	600,000				150,000
Electrical supply	50,000	50,000	50,000	50,000	50,000
Electro-mechanical works	1,100,000	135,000	700,000	100,000	800,000
Total capital cost, LE	**1,900,000**	**335,000**	**900,000**	**300,000**	**1,000,000**
2- Water production, m^3					
Annual production	750,000	750,000	750,000	750,000	750,000
Reused water in production process		75,000	125,000		
Net annual production, m^3	750,000	675,000	625,000	750,000	750,000
3- Expected lifetime for wells, years					
Wells	20	10 - 20	20	20	20
4- Annual depreciation, LE					
Wells	7,500	7,500 – 15,000	7,500	7,500	
Civil works	16,250	1,250	1,250	1,250	5,000
Electro-mechanical works	82,500	10,125	52,500	7,500	60,000
Total annual depreciation, LE	**106,250**	**18,875 – 26,375**	**61,250**	**16,250**	**65,000**
5- Operation and maintenance cost					
Salaries	11,800	6,250	11,800	6,250	11,800
Electricity	54,000	44,000	80,600	44,000	60,600
Civil works maintenance Electro-mechanical equipment	26,000	3,700	15,000	3,000	17,000
Treatment materials	1,500	1,500	5,500	1,500	7,500
Total annual O & M, LE	**93,300**	**55,450**	**112,900**	**54,750**	**96,900**
Total annual cost	**199,550**	**74,325 – 81,825**	**164,650**	**71,000**	**161,900**
Total production cost of 1 m^3 of water	**26,7**	**11 – 12,1**	**27,9**	**9,50**	**21,60**

- subsurface method is considered not complicated as regards implementation and operation, no chemicals are used in the process of iron and manganese removal by this approach. Also there is no continuous production of sludge as a result of removal operation.
- Ratio of water reused in this approach fluctuates between 10% and 15% from the produced water and is not considered a lost water.
- Subsurface method reliability is the same or nearly the same as groundwater plants which don't treat their water. It is also compatible with the existing groundwater plants regarding type of wells (shallow), mechanical and electrical tools, and available labor.
- subsurface method maintain pressure of well pumps and doesn't need additional pumps to pump water to the network.
- Investment cost of subsurface method for iron and manganese removal from groundwater is low compared to other available alternatives. It represents about 40% of the investment cost of using traditional methods to remove iron and manganese.
- Production cost of one cubic meter of water by using subsurface method is a little bit higher than the case of water supply without removing iron and manganese. It fluctuates between 11.0 and 12.1 piasters according to the estimated lifetime of the well, and is less than 50% of the production cost of water using the other alternatives.
- Applying subsurface method for iron and manganese removal from groundwater is considered to be much more simple than the other methods regarding component need for maintenance, special experiences, or size of installations and construction works.

ACKNOWLEDGEMENT

The author thanks El-Beheira Water Company (BWC) and its Chairman Mr. Mahmoud Mansour for their support and allowing him to evaluate and publish the project data.

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