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공학석사학위논문

**Design of Dual Water Supply System
Using Rainwater and Groundwater
at Arsenic Contaminated Area in Vietnam**

빗물과 지하수를 이용한 베트남의
용수공급시스템 개발

2013 년 2 월

서울대학교 대학원

건설환경공학부

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**Design of Dual Water Supply System
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at Arsenic Contaminated Area in Vietnam**

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**A dissertation submitted in partial fulfillment of the requirements
for the degree of Master in Civil and Environmental Engineering**

February, 2013

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College of Engineering
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Abstract

Design of Dual Water Supply System Using Rainwater and Groundwater at Arsenic Contaminated Area in Vietnam

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In Cukhe, a village located in the outskirts of Hanoi, the capital of Vietnam, people suffer from a shortage of high-quality water due to arsenic contaminated supply water resource. We found that a dual water supply of rainwater and groundwater is a suitable method to provide sustainable water to the local residents. Rainwater is supplied for potable purposes. Groundwater is supplied for non-potable purposes. In this paper, a novel model is developed based on rainfall variance. An Rainwater Harvesting (RWH) system can get optimal performance by changing demand of water use due to rainfall. This model is then used to assess the reliability and water savings of an RWH system for Cukhe village. Using rainwater for potable

purposes in dry days and for all purposes in rainy days is recommended. The cost of RWH systems was analyzed. In order to get 100% reliability, an RWH system has a roof area of 100m^2 and a tank size of 2m^3 is recommended in terms of cost efficiency. From the water supply chart in a year, it is recommended that rainwater should be supplied for only potable purposes in January-April and October-December; and should be supplied for all purposes in May-September.

The research also investigated arsenic removal from groundwater. A novel adsorbent Fe-Mn-Si oxide was prepared by coprecipitation from environmentally friendly and low-cost materials for effective arsenic removal and evaluated its arsenic adsorption capacities. Batch and column adsorption experiments were conducted to study efficiency adsorption of arsenic on Fe-Mn-Si oxide. Results from this study demonstrate the potential usability of Fe-Mn-Si oxide as a good arsenic-selective adsorbent.

Eventually, this research suggested water supply system options. There are three water supply system options namely: (1) rainwater supply system; (2) groundwater supply system and (3) Dual system which rainwater is used for drinking purposes and groundwater is used for non-drinking purposes. The triple bottom line considerations, the environmental, economical, and social impacts of the systems are examined. From the results it is clear that rainwater harvesting is a sustainable method to obtain good-quality drinking water at low cost and with little energy expenditure. A dual system, rainwater is supplied for drinking purposes and groundwater is supplied for

non-drinking purposes, is recommended in terms of engineering, social and economic benefits.

Keyword: Rainwater; Groundwater; Arsenic; Water supply; Developing country; Water management

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Contents

List of tables	I
List of Figures	II
Chapter 1. INTRODUCTION	1
1.1. Background.....	1
1.2. Objectives.....	1
1.3. Dissertation structure	3
1.4. Literature review.....	4
1.4.1. Rainwater harvesting	4
1.4.2. Arsenic removal	6
REFERENCES.....	10
Chapter 2. DESCRIPTION O AREA STUDY	13
2.1. Cukhe village.....	13
2. 2. The status of water sources	13
Chapter 3. DESIGN OF RAINWATER HARVESTING SYSTEM	16
3.1. INTRODUCTION	16
3.2. MATERIALS AND METHODS	18
3.2.1. Typical housing and current water supply system	18
3.2.2. Strategy for water supply.....	20
3.2.3. Cost analysis	24
3.2.4. Data	24
3.3. RESULTS AND DISCUSSIONS.....	25
3.4. CONCLUSION.....	30

REFERENCES.....	32
Chapter 4. GROUNDWATER TREATMENT	34
4.1. INTRODUCTION	34
4.2. METHODS AND MATERIALS	36
4.2.1. Adsorbent preparation	36
4.2.2. Arsenic solution.....	37
4.2.3. Experimental procedure.....	37
4.2.4. Analytical methods.....	39
4.3. RESULTS AND DISCUSSION.....	40
4.3.1. Characterization of adsorbent	40
4.3.2. Adsorption kinetics.....	41
4.3.3. Adsorption isotherms.....	44
4.3.4. Thermodynamic parameters.....	50
4.3.5. Effect of pH on arsenic adsorption.....	52
4.3.6. Desorption study	53
4.3.7. Fixed bed column for arsenic removal	54
4.4. CONCLUSION	58
REFERENCES.....	59
Chapter 5. SUGGESTION OF WATER SUPPLY SYSTEM.....	65
5.1. Description of water supply options	65
5.1.1. RWH system.....	65
5.1.2. Groundwater system.....	67
5.1.3. Dual system.....	68

5.2. Triple Bottom Line Consideration for Sustainable Water Supply	
69	
5.2.1. Environmental	69
5.2.2. Economic	70
5.2.3. Social	71
5.6. Conclusion.....	73
Chapter 6. CONCLUSIONS.....	74

List of tables

Table 3.1. Quality of water samples and WHO drinking water guideline

Table 4.1. First- and second-order kinetic parameters

Table 4.2. Langmuir, Freundlich, and D-R isotherm parameters

Table 4.3. Comparison of arsenic (III) adsorption capacity with some reported adsorbents.

Table 4.4. Calculated Thermodynamic parameters

Table 4.5. The total quantity of water treated in terms of bed volume before breakthrough and exhaust times

Table 4.6. Parameters for the fixed bed MCB column

Table 5.1. Cost analyses of available water supply options.

Table 5.2. Interview result about the water status in Cu Khe

List of Figures

- Fig. 1.1.** Structure of this dissertation
- Fig. 2.1.** The status of water sources in Cukhe village
- Fig. 3.1.** Current water supply system
- Fig. 3.2.** Dual water supply of rainwater and groundwater
- Fig. 3.3.** Schematic diagram of water flow in a rainwater tank
- Fig. 3.4.** Flow chart used to determine performance of an RWH system
- Fig. 3.5.** Daily rainfall data for the year 2005 from Hanoi city
- Fig. 3.6.** Variation of reliability (a) for low demand scenario (b) for demand is changed due to rainfall scenario and (c) for high demand scenario.
- Fig. 3.7.** Variation of water saving (a) for low demand scenario (b) for demand is changed due to rainfall scenario and (c) for high demand scenario.
- Fig. 3.8.** Variation of cost and reliability by tank size and roof area, for demand is changed due to rainfall scenario.
- Fig. 3.9.** Water supply chart, for four-household with an RWH system has a roof area of 100m^2 and a tank size of 2m^3 .
- Fig. 4.1.** Schematic diagram of fixed bed column.
- Fig. 4.2-**XRD analysis of Fe-Mn-Si oxide
- Fig. 4.3-**SEM micrograph
- Fig. 4.4.** Arsenic adsorption kinetic
- Fig. 4.5.** Pseudo-first-order kinetic
- Fig. 4.6.** Pseudo-second-order kinetic

Fig. 4.7-Arsenic isotherms on Fe-Mn-Si oxide

Fig. 4.8-Langmuir isotherm

Fig. 4.9. Freundlich isotherm

Fig. 4.10. D-R isotherm

Fig. 4.11- Effect of pH

Fig. 4.12. Desorption study

Fig. 4.13. Breakthrough curve for arsenic removal on Fe_Mn_Si oxide

Fig. 5.1. A general RWH system

Fig. 5.2. A general groundwater system

Fig. 5.3. Costs of available water supply options

Chapter 1. INTRODUCTION

1.1. Background

Fresh water, a renewable but limited resource, is scarce in many areas of the developing world because of unplanned withdrawal of waters from rivers and underground aquifers causing severe environmental problems. Like other developing countries, Vietnam is already facing water shortages. Especially in rural Vietnam, people did not have access to a safe water supply because of many problems. The government cannot afford the time and money to establish centralized water supplies. In addition, current water sources are contaminated: the river, groundwater and aquifers are contaminated with human waste and arsenic (Michael Berg 2001). Rainwater harvesting (RWH) is one of traditional methods as an alternative water source in rural Vietnam. However, there is no guidance for RWH management.

1.2. Objectives

The main objective of this study is to study supply safe water to the residents in which:

(1) Design of rainwater harvesting system

+) Propose the dual supply

(+) Design of rainwater systems at Cukhe using design chart

(2) Investigate arsenic removal from groundwater

(+) Preparation and characteristic of new adsorbent

(+) Batch Test

Study adsorption kinetics and isotherms

Study effect of pH

Study desorption

(+) Column test

Study adsorption column behavior

Study basic design parameters of adsorption

column

(3) Suggestion water supply system

(+) Analyze engineering technology aspect

(+) Analyze social aspect

(+) Analyze economic aspect

1.3. Dissertation structure

This study is composed of 6 chapters.

Chapter 1 contains the introduction, objectives, dissertation structure and literature review. Chapter 2 describes study area. Chapter 3 includes determination of RWH system performance. Chapter 4 investigates arsenic removal on novel adsorbent Fe-Mn-Si oxide. Chapter 5 includes suggestion water supply system. Chapter 6 contains a conclusion of this study and recommendations. The structure of this study is shown in Figure 1.1.

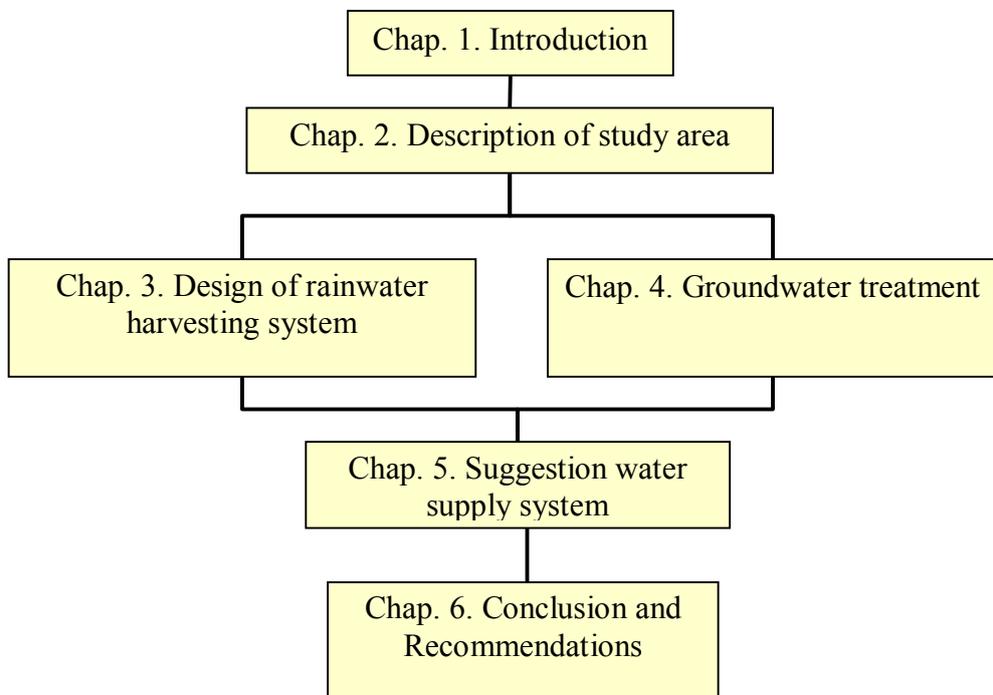


Figure 1.1. Structure of this dissertation

1.4. Literature review

1.4.1. Rainwater harvesting

Due to pollution of both groundwater and surface waters, and the overall increased demand for water resources due to population growth, many communities all over the world are approaching the limits of their traditional water resources. Therefore they have to turn to alternative or ‘new’ resources like rainwater harvesting (RWH). Rainwater harvesting has regained importance as a valuable alternative or supplementary water resource. Utilization of rainwater is now an option along with more ‘conventional’ water supply technologies, particularly in rural areas, but increasingly in urban areas as well. RWH has proven to be of great value for arid and semi-arid countries or regions, small coral and volcanic islands, and remote and scattered human settlements. Rainwater harvesting has been used for ages and examples can be found in all the great civilizations throughout history. The technology can be very simple or complex depending on the specific local circumstances. Traditionally, in Vietnam rainwater is collected from roofs, using bamboo as gutters. With the increasing availability of corrugated iron roofing in many developing countries, people often place a small container under their eaves to collect rainwater. Many individuals and groups have taken the initiative and developed a wide variety of different RWH systems throughout the world.

1.4.1.1. Methods of Modeling the Hydrological Performance of Rainwater Harvesting Systems

There are numerous methods available for predicting the performance of RWH systems and these range from the relatively simple, such as “rule-of-thumb” approaches to the more complex, such as statistical methods and sophisticated computer programs. Existing techniques vary in comprehensiveness. Some explicitly consider only one or a small number of RWH system components, such as the catchment area (rainfall/runoff characteristics) or the primary storage tank, whilst others include the explicit assessment of a wider range of components. Evaluation at different spatial scales is also possible. Some methodologies are concerned only with RWH system performance at the level of a single building whilst others seek to investigate the impacts of wider implementation, such as at the development or catchment scale (e.g. Liu et al, 2005; Sakellari et al, 2005; Sekar & Randhir, 2006), often with the aid of Geographical Information Systems (GIS), (Prakash & Abrol, 2005; Kahinda et al, 2006). Some methodologies focus solely on hydrological performance whilst others include additional elements such as economic/financial measures (e.g. Coombes et al, 2002, 2003b; Liaw & Tsai, 2004; Ghisi & Oliveira, 2007) and in some instances an assessment of system “sustainability” (Parkinson et al, 2001; Vleuten-

Balkema, 2003); Anderson, 2005; Sakellari et al, 2005).

The use of computer software for modeling the hydraulic behavior of both traditional (piped) urban drainage systems and SUDS is now common practice amongst drainage engineers and researchers (e.g. Swan et al, 2001; Kellagher et al, 2003; Millerick, 2005a). Computer based methods offer a number of advantages over manual calculations, such as much greater speed and flexibility, sophisticated data handling capabilities, simulation of specific designs under a wide range of circumstances, optimization, and assessment of associated risk and identification of potential failure routes. Many RWH system models are also computer based and the majority of the existing research reviewed made reference to the use of software-based techniques.

1.4.2. Arsenic removal

1.4.2.1. Principles of adsorption

A solid surface in contact with solution tends to accumulate a surface layer of solute molecules because of the unbalance of the surface forces. Chemical adsorption results in the formation of mono molecular layer of the adsorbate on the surface through forces of residual valence of the surface molecules. Physical adsorption results from molecular condensation in the capillaries of the solid. In general substances of the highest molecular

weight are most easily adsorbed (9). Morris and Weber found the rate of adsorption to vary as the square root of the time of contact, as shown in below:

Influence of molecular structure and other factors on adsorbability

- 1) An increasing solubility of the solute in the liquid carrier decreases its adsorbability.
- 2) Branched chains are usually more adsorbable than straight chains. An increasing length of the chain decreases solubility.
- 3) Substituent groups affect adsorbability:

Hydroxyl	Generally reduces adsorbability. Extent of decrease depends on the structure of host molecule.
----------	--

Amino	Effect varies according to host molecule. Glyoxylic acid more adsorbable than any other acids are not adsorbed to any appreciable extent.
-------	---

Carbonyl	Effect varies according to host molecule. Glyoxylic acid more adsorbable than acetic but similar increasing does not occur when introduced into higher fatty acids.
----------	---

Double bonds	Variable effects as with carbonyl
--------------	-----------------------------------

Halogens	Variable effects
----------	------------------

Sulfonic	Usually decreases adsorbability
Nitro	Often increases adsorbability

4) Generally, strong ionized solutions are not as adsorbable as weakly ionized ones

5) The amount of hydrolytic adsorption depends on the ability of the hydrolysis to form an adsorbable acid or base

6) Unless the screening action of the carbon pores intervenes, large molecules are more sorbable than small molecules of similar chemical nature. This is attributed to more solute carbon chemical bonds being formed, making desorption more difficult (10).

7) Molecules with low polarity are more sorbable than highly polar ones.

a) Langmuir isotherm

The degree to which adsorption will occur and the resulting equilibrium relationships have been correlated according to the empirical relationship of Freundlich and the theoretically derived Langmuir relationship. The Langmuir equation is based on equilibrium between condensation and evaporation of adsorbed molecules, considering a monomolecular adsorption layer:

$$q_e = (q_m K_L C_e) / (1 + K_L C_e) \quad (1)$$

where q_e is the amount of arsenic adsorbed on per gram of adsorbent (mg/g), C_e is the total arsenic concentration of solution (mg/L), K_L is the equilibrium adsorption constant related to the affinity of binding sites (L/mg), and q_m is the maximum amount of the arsenic per unit weight of adsorbent for complete monolayer coverage. Since most wastewaters contain more than one substance which will be adsorbed, direct application of the Langmuir equation is not possible. More complex relationships could similarly be developed for multicomponent mixtures. It should be noted that although the equilibrium capacity for each individual substance adsorbed in a mixture is less than that of the individuals alone.

b) Freundlich isotherm

The Freundlich isotherm curves in the opposite way of the Langmuir isotherm and is exponential in form. It often represents an initial surface adsorption followed by a condensation effect resulting from extremely strong solute-solute interaction. In chromatography the Freundlich isotherm is not common; most adsorption processes are best described by the Langmuir. For practical application, the Freundlich isotherm usually provides a satisfactory correlation. The Freundlich isotherm is expressed as:

$$q_e = k_f C^{1/n} \quad (2)$$

where k_f is the Freundlich constant indicative of the adsorption intensity of the adsorbent, n is the experimental constant indicative of the adsorption intensity of the adsorbent.

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Chapter 2. DESCRIPTION OF AREA STUDY

2.1. Cukhe village

Cukhe is a remote village near by Hanoi, Vietnam. It has Latitude 20°56'7"N and Longitude 105°47'45"E. The mean daily temperature is about 28 °C. It covers a geographic area of 5.76 km² and has a population of 4667 inhabitants. The government cannot afford the time and money to establish centralized water supply to the village. In addition to, the current water sources are being contaminated by many problems; hence, there is a need to develop other water sources.

2. 2. The status of water sources

The current sources are river water, groundwater and rainwater.

River water: Twenty years ago, local residents used to go to the Nhue River to swim or wash clothes. They sometimes took surface water to empty into the jars or small tanks and used the aluminium alum to settling particles. They then used such clean water to cook. They are unable to do so nowadays because the River is seriously polluted by wastewater of Hanoi city (Fig. 2.1 a).

The concentration of BOD is expected to be equal 1,620,000 and

2,218,750 kg/day in 2010 and 2020, respectively. The COD are 1,360,000 and 1,850,000 kg/day and SS are 1,100,000 and 1,481,250 kg/day. Another parameters concentration are also higher than standard such as: nickel (Ni), chromium (Cr), lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd) are 1.24-7.74, 1.51-6.45, 0.28-1.97, 1.66-2.31, 25.19-77.94, 0.06-0.14, ($\mu\text{g/l}$), respectively.

Currently, local residents only use ground water and rainwater in daily livings.

Groundwater: Groundwater is the main water source in Cu Khe village. Most of households own a depth well (Fig. 2.1 b). The depth of wells is about 34 – 40 meters and wells were made by manual drill equipment. Households use electric pumps to take the groundwater and treat it by simply system. Normally, groundwater is used for washing and showing. But it is also used for drinking and cooking during dry season. The cost to exploit the ground water only includes the cost for electrical of pump, and it accounts for 10 percent of the household's total electrical cost. Nevertheless, ground water is also polluted by arsenic toxic. The arsenic concentration is greater than Vietnams' standard of eight to ten times. This is a huge problem for local residents, especially poor households.

Rainwater: Rainwater was the most trusted potable water. There were some problems with the existing rainwater harvesting system in Cu Khe village. There was no catchment management and filtration in the system.

Therefore, the bottom of the storage tanks always exist a sludge layer and it could become the good environment for mosquitoes or insect growth. This accounts for the water quality in the rainwater storing tank.



a, Surface water

b, Groundwater system



c, Rainwater system

Figure 2.1. The status of water sources in Cu Khe village

Chapter 3. DESIGN OF RAINWATER HARVESTING SYSTEM

3.1. INTRODUCTION

Fresh water, a renewable but limited resource, is scarce in many areas of the developing world. This is due to unplanned withdrawal of waters from rivers and underground aquifers which causes severe environmental problems such as arsenic contamination (Michael Berg, 2001).

In Cukhe village, people do not have access to a safe water supply because of many problems. The government cannot afford the time and money to establish centralized water supplies. In addition, current water sources are contaminated: the river, groundwater and aquifers are contaminated with human waste and arsenic. Therefore, it is urgent to promote alternative water supply options to the traditional water sources. We find out that a dual water supply of rainwater and groundwater is a suitable method to provide sustainable water to the local residents. The reasons are that: First, rainwater harvesting was one of the most popular traditional methods in villages of Vietnam. Second, rainwater quality is good, it can be supplied for potable purposes; groundwater had a low turbidity but very high a concentration of heavy metals. Hence, it can be supply for non-potable purposes such as toilet flushing...

Many researchers have attempted to promote significant potable water savings by rainwater (Handia et al. 2003); (Ghisi et al. 2007); (Muthukumaran et al. 2011); (Amin and Han.2009). There are a numerous methods available for predicting the performance of RWH systems. A model to determine the effectiveness of rainwater tanks and stormwater runoff using long term historical rainfall data has been developed by Vaes and Berlamont (2001). A computer model for the continuous simulations of amount of rainwater stored in the tank, amount of rainwater used, amount overflowed and amount of mains top up for household rainwater tanks has been developed by Jenkins (2007); Mun and Han (2012) developed a design and evaluation method for a RWH system to improve the operational efficiency based on sensitivity analysis.

These modelling are generally focussed on developed countries, where water scarcity is usually a matter of economics rather than basic human health. Moreover, previous researchers did not take into account rainfall variance which can improve the performance of an RWH system. Rainwater can be supplied for a high demand of water use in rainy season. The same cannot happen in dry season.

This paper proposes the dual water supply of rainwater and groundwater to provide sustainable water. A novel modelling is developed considering rainfall variance. They are employed to design RWH system at Cukhe village.

3.2. MATERIALS AND METHODS

3.2.1. Typical housing and current water supply system

Typical roof materials are made from brick, galvanized iron sheeting and asbestos with an average roof area of 50m².

There are two kinds of water supply systems in Cukhe: groundwater systems and rainwater harvesting systems and they have different structures and forms (Figure 1).

A groundwater system includes filters and a storage tank. Filters consist of a sand layer, gravel layer, and activated carbon layer which are housed on the storage tank in a concrete structure with average dimensions of about 100 cm width, 200 cm length, and 85 cm height. The filter is cleaned monthly by residents, and all filter layers are replaced with new layers twice a year. However, the filter used by the lower socioeconomic class is different. It comprises a tin can of 47 cm radius and 45 cm height filled with sand and an activated carbon layer. This filter is expected to have the disadvantages of having less filter material and being harder to recover. Pumped up groundwater is stored in the storage tank after being filtered by an installed filter, after which it is potable. The filter efficiency for the groundwater system affects the water quality, and thus periodic cleansing and changing of the filter is an important attribute. However, the lower

socioeconomic class, who have suffered from diseases owing to the use of groundwater without the periodic cleansing and changing of filters, do not trust the potable use of groundwater.

The rainwater system comprises a rooftop as a collection area and a reservoir tank. Each house has a 1–6-ton rainwater reservoir installed. Water collected by the rooftop fills the reservoir via guttering. Rainwater collected during the monsoon season is used even during the dry season, but when the stored amount is insufficient, groundwater is used. There are many differences in the groundwater system design and form for those of different socioeconomic status, but the use of rainwater is almost the same. The rainwater system is economical because there is no need to change filters or purchase a pump. In addition, because the system does not require a filter change, the pump uses little energy and the utility value is high.



Fig. 3.1. Current water supply system. Rainwater system (left) and groundwater system (right)

3.2.2. Strategy for water supply

3.2.1.1. Dual system according to water quality

The water quality from various sources was tested and compared. For the test, samples were taken from three wells and rainwater storage tanks at three sites. A 2100P Potable Turbidity meter by HACH was used to test turbidity and a pH meter was used to test pH, temperature and conductivity (EC). The water quality of the representative samples was analysed at the Vietnam Institute of Environmental Technology upon completion of the research trip. The water quality analysis considered 17 heavy metals (As, Be, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Sb, Se, Ti, and Zn), six negative ions (F, Cl, NO₂, NO₃, PO₄, and SO₄) and the amount of total suspended solids.

The results are shown in Table 3.1 and are compared with the WHO drinking water guideline. Groundwater had a low turbidity but very high concentration of heavy metals (Arsenic) and NO₂. Hence, it can be supplied for non-potable purposes. Meanwhile, the rainwater is far less than that in listed in WHO drinking water guideline. It can be supplied for potable purposes. Because rainwater quantity is not enough for all purposes, a dual water supply of rainwater and groundwater as shown in Fig. 3.2. is recommended.

Table 3.1. Quality of water samples and WHO drinking water guideline

Site		Alley 14-Khuchthuy		Kindergarten		Quangtrung WH alley O	
Parameters	Unit	Groundwater	Rainwater	Groundwater	Rainwater	Groundwater	
Temp	0C	17.9	19.3	21.8	19.5	18.1	-
PH		7.09	6.89	7.07	7.5	6.48	-
Turbidity	NTU	0.97	2.75	1	1.96	1.77	5
EC		596	99.5	720	98.5	592	-
As	mg/10.042	0	0.03	0	0.035	0.01	
Cu	mg/10.005	0	0.012	0.004	0.008	0.003	1
Fe	mg/10.055	0	0.035	0.016	0.028	1.758	-
Ni	mg/10.002	0	0.002	0	0.002	0.002	0.02
Pb	mg/10.005	0	0.005	0.006	0.003	0.004	0.01
Zn	mg/10.003	0	0.124	0.011	0.07	0.003	3
NO ₂	mg/112.511	1.93	27.644	0.177	0.333	3	
NO ₃	mg/10.029	0	0.078	3.725	7.347	50	

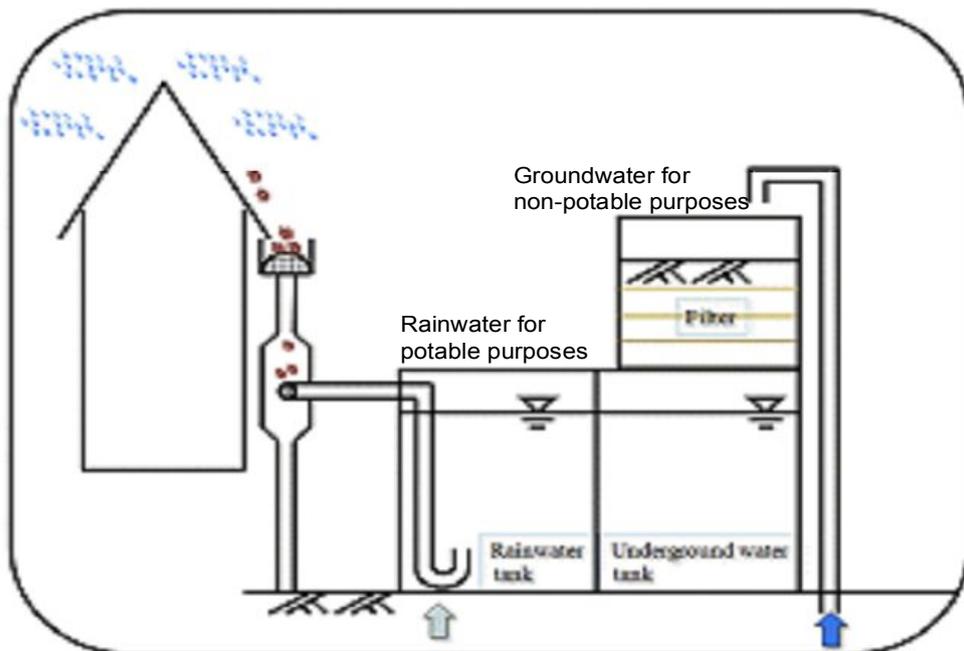


Fig. 3.2. Dual water supply of rainwater and groundwater

3.2.1.2. Design and evaluation method for RWH systems

The design and performance efficiency of an RWH system is based on the daily mass balance considers various factors such as tank size, daily rainfall, losses, daily water demand, mains top up and overflow as shown in Fig. 3.3.

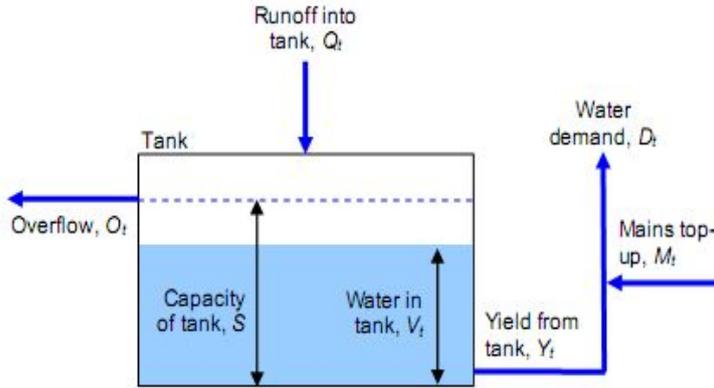


Fig. 3.3. Schematic diagram of water flow in a rainwater tank

The overall process can be mathematically described as follows:

Cumulative water storage equation:

$$V_t = V_{t-1} + Q_t - D_t \quad (1)$$

$$V_t = 0, \text{ for } V_t < 0 \quad (2)$$

$$V_t = S, \text{ for } V_t > S \quad (3)$$

where V_t is the cumulative water stored in the rainwater tank (m^3) after the end of t^{th} day, Q_t is the harvested rainwater (m^3) on the t^{th} day, V_{t-1} is the storage in the tank (m^3) at the beginning of t^{th} day, D_t is the daily rainwater demand (m^3) of t^{th} day. The daily demand is determined based on the rainfall variance: in rainy days, the daily demand is the maximum demand (rainwater is used for all purposes); in dry days, the daily demand is the

minimum demand (rainwater is used only for potable purposes). S is the capacity of rainwater tank (m^3).

Groundwater use equation;

$$G_{w,t} = D_t - V_t, \text{ for } V < D_t \quad (4)$$

where $G_{w,t}$ is the groundwater use on t^{th} day (m^3).

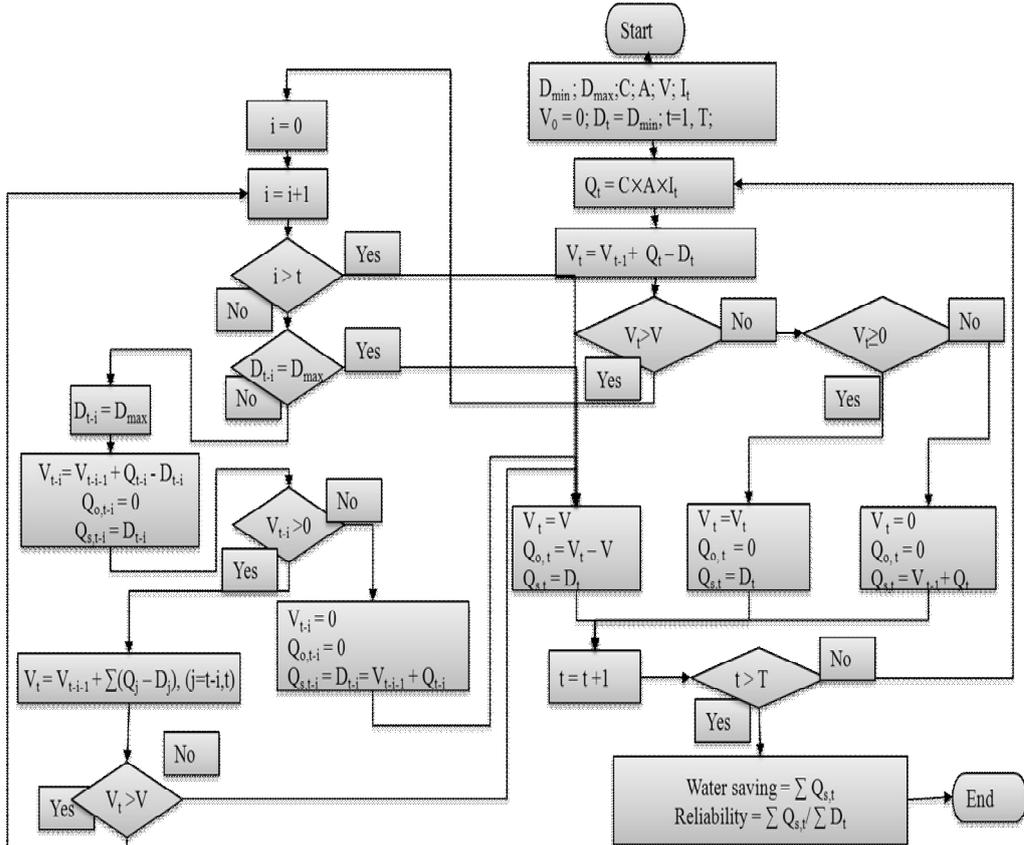


Fig. 3.4. Flow chart used to determine performance of an RWH system. A is the roof area (m^2). C is the collection efficiency. T is the simulation period. I_t is daily rainfall of t^{th} day (mm/day). D_{\min} is the minimum demand and D_{\max} is the maximum demand.

The reliability (R_e) and water saving (WS) were defined and employed to design and evaluate the RWH system performance. R_e is the reliability of the tank to be able to supply intended demand $D_t(\%)$. WS is the total

rainwater supplied. The parameters of the RWH system under various factors were calculated through computer simulation using the algorithm shown in Fig. 3.4.

3.2.3. Cost analysis

The cost of an RWH system can be determined as follow:

$$C = C_S * S + C_R * R + C_I \quad (5)$$

where C_S is the cost of the storage tank per m^3 . S is the storage tank size (m^3). C_R is the cost of the expanded roof area per m^2 . R is the expanded roof area (m^2). C_I includes both materials/equipment and installation costs.

3.2.4. Data

For this study, daily rainfall data was collected from Hanoi city for a typical dry year of 2005. It should be noted that the long-term annual average rainfall for the city is 1800 mm, whereas in 2005 the total annual rainfall was 1594 mm. Fig. 3.5 shows the rainfall time series for the year 2005, starting from 1st January. A range of tank size from 0 - 10,000 (L) were considered. In regards to roof area, 0 - 350 m^2 were considered. Three demand scenarios were selected, namely: (a) low demand; for potable purposes only, which is 60L per day per household; (b) high demand; for all purposes, which is 200 L per day per household; and (c) demand is changed

due to rainfall; for potable purposes in dry days and for all purposes in rainy days.

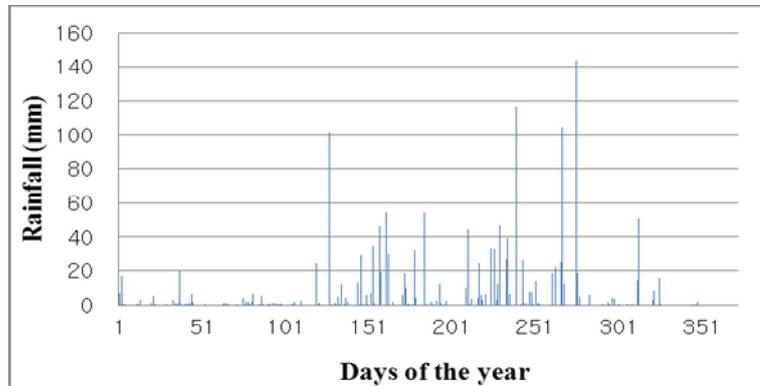


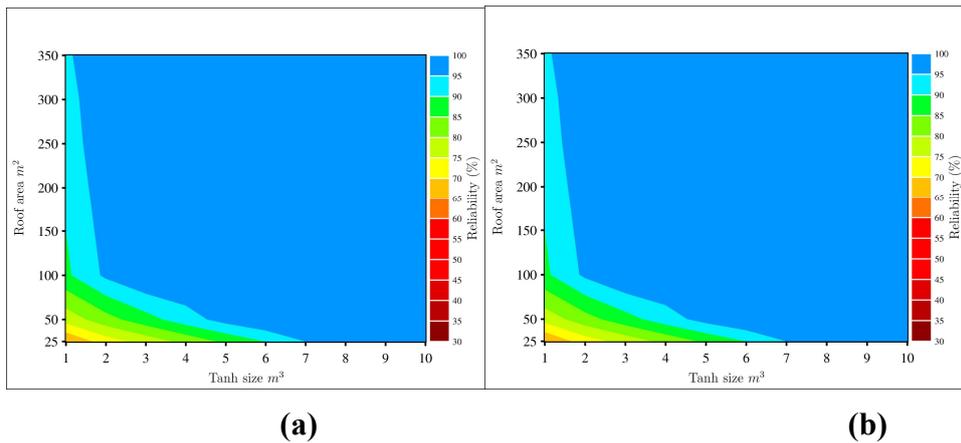
Fig. 3.5. Daily rainfall data for the year 2005 from Hanoi city

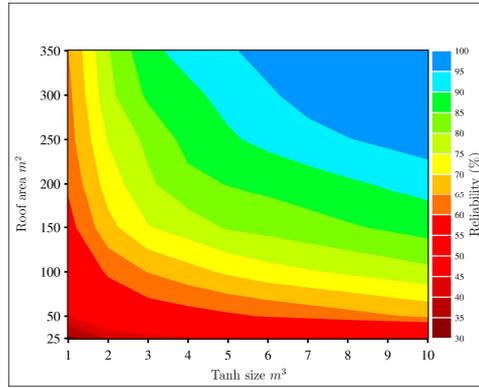
3.3. RESULTS AND DISCUSSIONS

Fig. 3.6 shows the variation of the reliability varying with tank sizes and roof areas under different demand scenarios ((a) for low demand scenario; (b) for demand is changed due to rainfall scenario; and (c) for high demand scenario). From the figure it is clear that the reliability increases with an increase in tank size or roof area. With a tank size and a roof area, the reliability of low demand scenario is equal the reliability of the scenario which demand is changed due to rainfall, and significantly higher than the reliability of high demand scenario. For low demand and demand is changed due to rainfall scenarios, 100% reliability can be achieved for a tank size of 8m^3 with a roof area of 25m^2 . The tank size can be decreased to 2m^3 with an upon roof area of 150m^2 . For high demand scenario, 100% reliability can be

achieved for a tank size of 10m^3 with a roof area of 250m^2 . The tank size can be decreased to 6m^3 with an upon roof area of 350m^2 .

Fig. 3.7 shows the variation of the water saving varying with tank sizes and roof areas under different demand scenarios ((a) for low demand scenario; (b) for demand is changed due to rainfall scenario; and (c) for high demand scenario). It is found that the water saving can be increased with an increase in tank size or roof area. With a tank size and a roof area, the water saving of high demand scenario is equal the water saving of the scenario which demand is changed due to rainfall, and significantly higher than the water saving of low demand scenario.

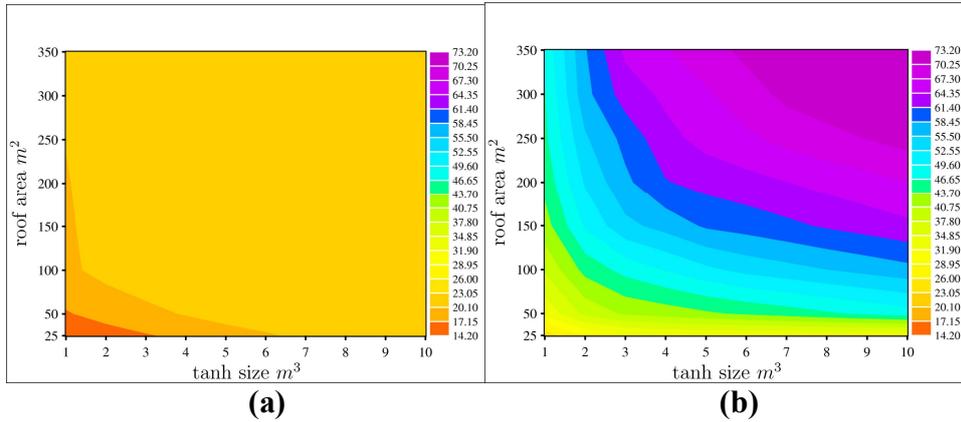




(c)

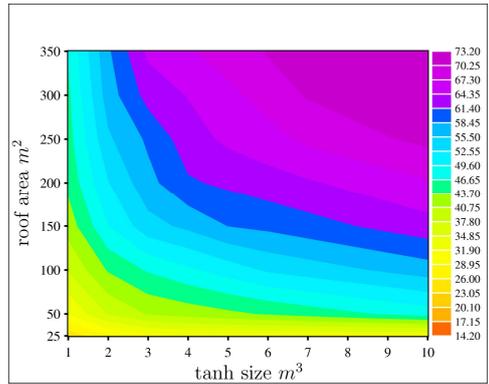
Figure 6. Variation of reliability (%), (a) for low demand scenario (b) for demand is changed due to rainfall scenario and (c) for high demand scenario.

From the results it is clear that an RWH system can get optimal performance if demand is changed due to rainfall. Using rainwater for portable purposes in dry days and for all purposes in rainy days is recommended.



(a)

(b)



(c)

Fig. 3.7. Variation of water saving (a) for low demand scenario (b) for demand is changed due to rainfall scenario and (c) for high demand scenario.

Fig.3.8. shows variation of cost and reliability by tank size and roof area, for demand is changed due to rainfall scenario. In order to get 100% reliability, an RWH system has roof area of 100m² and tank size of 2m³ is recommended in terms of cost efficiency.

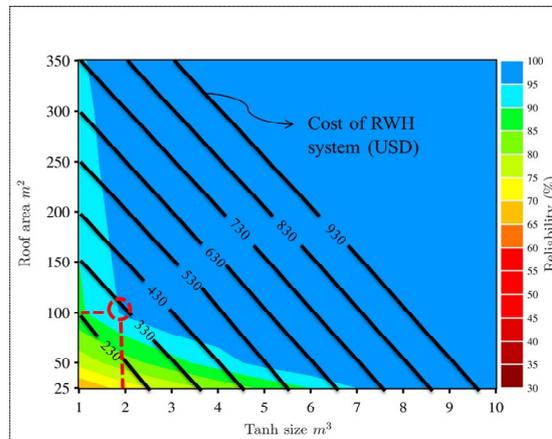


Fig. 3.8. Variation of cost and reliability by tank size and roof area, for

demand is changed due to rainfall scenario.

Fig. 3.9. shows the water supply chart for a four-household with an RWH system has a roof area of 100m^2 and a tank size of 2m^3 . From the results, it is recommended that rainwater should be supplied for only potable purposes in January-April and October-December; and should be supplied for all purposes in May-September.

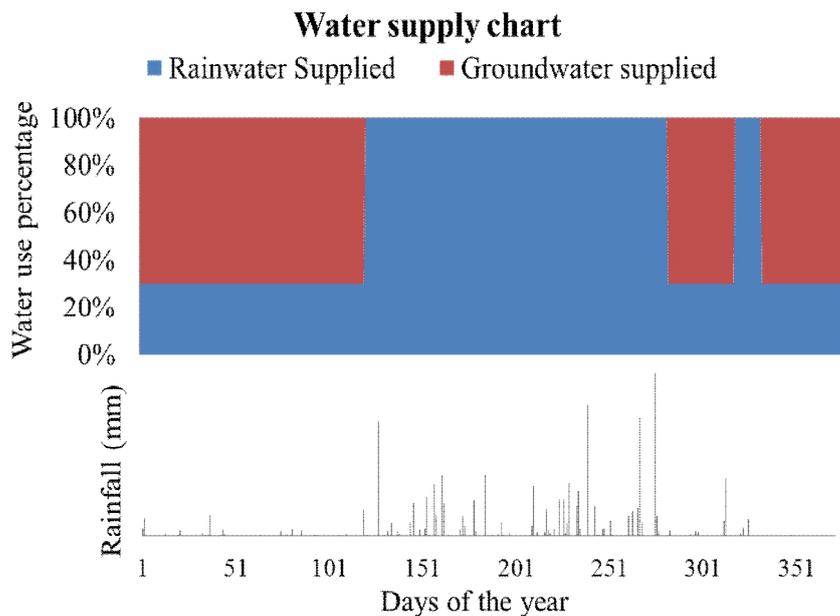


Fig. 3.9. Water supply chart, for four-household with an RWH system has a roof area of 100m^2 and a tank size of 2m^3 .

3.4. CONCLUSION

This paper investigated water supply solutions for Cukhe village – a contaminated area. The dual water supply of rainwater and groundwater is recommended. Rainwater quality is good; it can be supplied for potable purposes. Groundwater is low turbidity but too high a concentration of heavy metal (As); it can be supplied for non-potable purposes.

In this paper, a novel simulation chart is developed based on rainfall variance and is then used to analyze RWH system performance. An RWH system can get optimal performance if demand is changed due to rainfall. Using rainwater for portable purposes in dry days and for all purposes in rainy days is recommended. Cost of RWH systems is analyzed. In order to get 100% reliability, an RWH system has a roof area of 100m^2 and a tank size of 2m^3 is recommended in terms of cost efficiency. For a four-household with an RWH system has a roof area of 100m^2 and a tank size of 2m^3 , it is recommended that rainwater should be supplied for only potable purposes in January-April and October-December; and should be supplied for all purposes in May-September.

In addition, this study has demonstrated that rainwater harvesting can save a significantly amount of water from mains top up, even in dry years in Vietnam. These findings highlight the value of rainwater harvesting if it is fully implemented as a water management strategy in Vietnam.

The design and evaluation method proposed in this paper will be useful in evaluating and comparing the performance of RWH system for other areas. They can be applied to other regions using site-specific conditions.

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Chapter 4. GROUNDWATER TREATMENT

4.1. INTRODUCTION

Arsenic pollution has become a dominant environmental concern in recent years because of its adverse effect on human health. Arsenic is a known carcinogen that causes skin, lung, bladder, liver, kidney, and prostate cancers (Boddu et al. 2008). Several studies have reported that chronic health problems related to arsenic primarily stem from the consumption of arsenic-contaminated drinking water. These problems have been widely reported all over the world, for instance, in Argentina (Smedley et al. 2002), Bangladesh (Karim 2000), China (Xia and Liu 2004), Chile (Caceres et al. 2005), India (Roychowdhury et al. 2002), Japan (Kondo et al. 1999), Mexico (Cebrian et al. 1983), Nepal (Shrestha et al. 2003), New Zealand (McLaren and Kim 1995), Taiwan (Xia and Liu 2004), USA (Burkel and Stoll 1999), and Vietnam (Berg et al. 2001). Arsenic exists predominantly in inorganic anion forms, AsO_3^{3-} (III) and AsO_4^{3-} (V), in natural water and thus in drinking water, its solubility in soil mainly depending on redox potential and pH conditions. The World Health Organization has set a provisional guideline limit of $10 \mu\text{g l}^{-1}$ for arsenic in drinking water (WHO).

Arsenic contamination or enrichment in natural water can come from both natural processes, such as weathering of arsenic minerals, and

anthropogenic activities including mining, smelting of non-ferrous metals, burning of fossil fuel, industrial waste discharge, and application of arsenic herbicides and pesticides. The conventional techniques for removal of arsenic from water include precipitation/coprecipitation, ion exchange, membrane filtration, and adsorption (E.O. Kartinen 1995), (Bacocchi et al. 2005), (Boccelli et al. 2005), (Sancha 2006), (Manju et al. 1998). These techniques efficiently remove arsenic from drinking water but require toxic and expensive chemicals and generate a large amount of exhaust sludge, which is not always regenerable. Adsorption is considered to be one of the most promising of such technologies because an adsorption system can be cost-effective and simple to operate.

Various adsorbents for arsenic removal from water have been developed, which include such materials as activated carbon (Jang et al. 2008), activated alumina (Singh and Pant 2004), granular ferric hydroxide (Banerjee et al. 2008), hydrous ferric oxide (Wilkie and Hering 1996), iron oxide coated sand (Thirunavukkarasu et al. 2003), iron hydroxide coated alumina (Hlavay and Polyak 2005), GAC, Fe (III) oxide impregnated GAC (Mohan and Pittman Jr 2007), and Goethite (Ladeira and Ciminelli 2004). These adsorbents have been reported to efficiently remove arsenic from water; however, most of these adsorbents still involve several problems in terms of efficiency and cost. Thus, there still remains a strong challenge in developing novel adsorbents for arsenic removal with high uptake and

regeneration efficiency, low cost, and excellent physical and chemical durability.

Our aim is to find a novel, cost-effective adsorbent for arsenic removal. Iron and manganese oxides are reported as effective adsorbents for arsenic removal. Silica is mainly used for iron oxide modification in order to improve the adsorption performance due to the high surface area and high concentration of reactive surface sites. To the best of our knowledge, no research on Fe-Mn-Si oxide for arsenic removal has been reported in the literature. The main objectives of the present research were to prepare Fe-Mn-Si oxide by coprecipitation from environmentally friendly and low-cost materials for effective arsenic removal and to evaluate its arsenic adsorption capacities.

4.2. METHODS AND MATERIALS

4.2.1. Adsorbent preparation

In the laboratory, Si was added to ferric manganese oxide through a coprecipitation process. Ferric chloride (FeCl_3 , 7.31 g) was dissolved in 200 mL of distilled water. Ferrous sulphate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 12.51 g) and anhydrous silicon dioxide (SiO_2 , 18g) were then added to this solution. Potassium permanganate (KMnO_4 , 2.37 g) solution was prepared by dissolving KMnO_4 in 200 mL of distilled water. Iron and silicon were added

to the potassium permanganate solution with vigorous stirring, and 1 M NaOH solution was added to it to adjust the pH to approximately 4–5. The solution was then stirred continuously for 1 h. After 4 h, a precipitate was formed at room temperature and was separated from the liquid portion. The sedimentation-containing liquor was then dried at 90 °C for 12 h. The dried adsorbent, which was dark brown in color, was powdered and stored in desiccators for later use.

4.2.2. Arsenic solution

The standard stock As(III) solution (1000 mg/L) was prepared by dissolving an appropriate quantity of arsenic trioxide (As_2O_3) in distilled water containing 1% (w/w) NaOH; this solution was then diluted up to 1 L with de-ionized water. The working solutions of As(III) of a required concentration were made by diluting the stock with de-ionized water.

4.2.3. Experimental procedure

The adsorption experiments were carried out in batch conditions where 0.5 g of adsorbent was added to 100-mL HDPE bottles containing 50 mL of a working solution of known ion species and concentrations. The effect of different pH values on arsenic adsorption was studied by adjusting the pH of the solution to the required pH range of 2.0–10.0 using either 0.1M HCl or

0.1M NaOH solutions. The bottles were settled in an incubator shaker and continuously shaken at 160 rpm for a predetermined time period. The reaction temperature was set in the range of 25–45 °C. After the predetermined adsorption time, solid and liquid phases were separated using a 0.45µm membrane filter, and arsenic concentrations in the liquid phase were measured. The adsorption capacity, q (mg/g), was calculated using the following mass balance equation:

$$q = \frac{V(C_0 - C)}{W} \quad (1)$$

where C_0 and C are, respectively, the initial and final liquid-phase concentrations of arsenic (mg/L). V is the volume of solution (L); and W , the dry weight of adsorbent used (g).

For the desorption study, arsenic-loaded Fe-Mn-Si oxide was separated from the solution by filtration after the adsorption experiment, washed with deionized water, and dried at 110 °C. 0.5 g of dried arsenic-loaded Fe-Mn-Si oxide was added to 50 mL of 0.01–0.2 N NaOH in an HDPE bottle, and the bottle was then shaken at 160 rpm for 4 h at 25 °C. The final concentration of arsenic in the desorption medium separated by filtration was determined. The percentage of desorption was calculated from the amount of arsenic loaded on Fe-Mn-Si oxide and the final concentration of arsenic in the desorption medium.

Fixed-bed column study was conducted using a column of 1 cm diameter and 10 cm length. The column was packed with Fe-Mn-Si oxide and the

depth was 8 cm (Fig. 4.1). The column was charged with initial As(III) concentration of 1 mg/L in the up-flow mode with a volumetric flow rate of $1.92 \text{ m}^3/(\text{m}^2 \text{ h})$ (10 ml/min). The current flow rate was chosen to have sufficient amount of effluent water per hour for practical purpose. This range is also common for column design. The samples were collected at certain time intervals and were analyzed for the remaining arsenic concentrations.

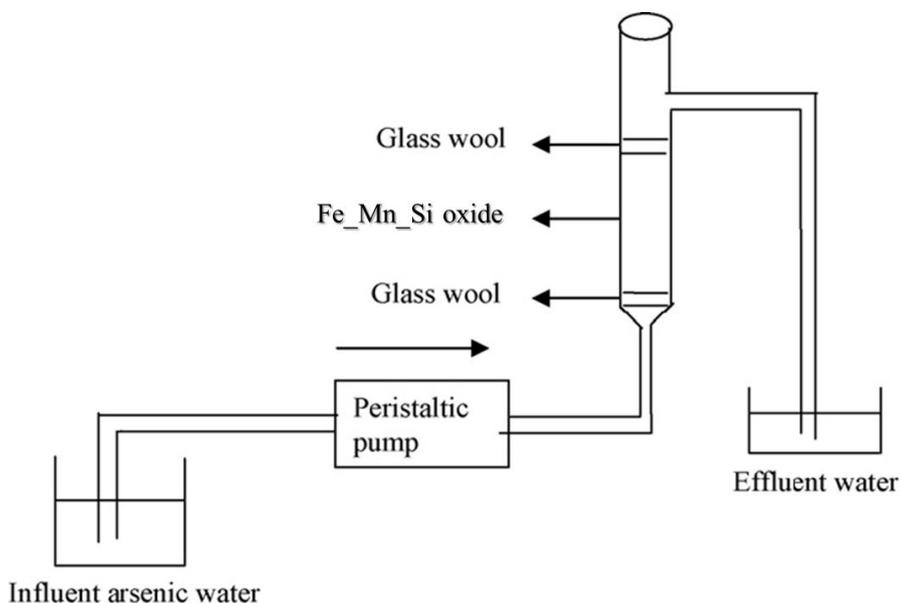


Fig. 4.1. Schematic diagram of fixed bed column.

4.2.4. Analytical methods

ICP-730ES was employed to determine the arsenic concentration throughout the experiment. The point of zero charge (pH_{zpc}) was determined

from a zeta potential analyzer (Zeta-Meter, USA) under different pH conditions. The background electrolyte of the solutions was 100 mg/L NaCl to maintain constant ionic strength.

4.3. RESULTS AND DISCUSSION

4.3.1. Characterization of adsorbent

The zeta potential of Fe-Mn-Si under different pH conditions decreased with increasing pH. The zero point of charges (pH_{zpc}) of Fe-Mn-Si was 3.3.

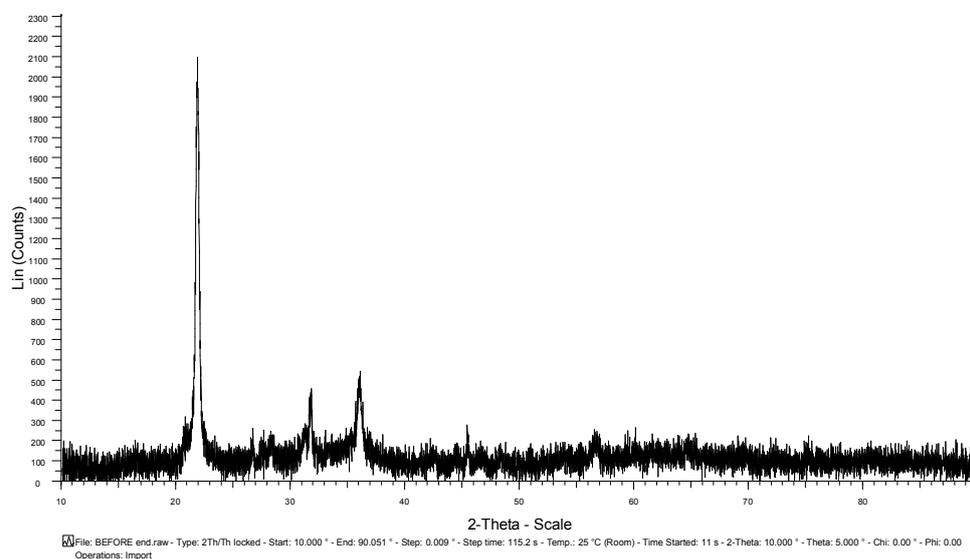


Fig. 4.2-XRD analysis of Fe-Mn-Si oxide

The mineral constitution of the adsorbent was investigated through powder X-ray diffraction using an X'Pert Pro XRD system diffractometer with a curved position-sensitive detector configured in vertical geometry

with a 2-theta detection range, operated at 40 mA and 40 kV. The results are shown in Fig. 4.2. Obvious peaks at 22°, 28°, 32°, 36°, 46°, 57° were observed. Peaks at 22° and 32° are the characteristic peaks of Fe and are assigned to the (110) and (221) planes of Fe, respectively. Peaks at 28° and 57° are the characteristic peaks of Si and are assigned to the (111) and (311) planes of Si, respectively. Peaks at 36° and 46° are the characteristic peaks of Mn and are assigned to the (221) and (400) planes of Mn, respectively.

Scanning electron microscopy (SEM) was used to study the morphology and surface element distribution of the Fe-Mn-Si oxide adsorbent. The image obtained for the Fe-Mn-Si oxide adsorbent is shown in Fig. 4.3. The surface of the adsorbent is rough and porous.

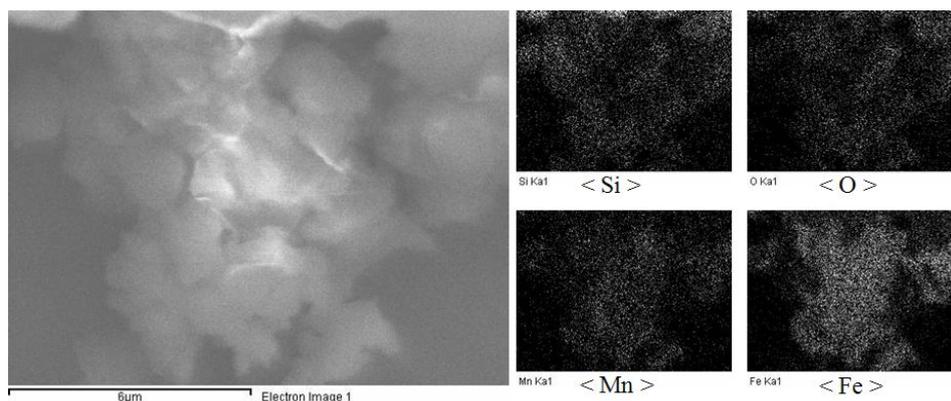


Fig. 4.3-SEM micrograph

4.3.2. Adsorption kinetics

Batch experiments were conducted to determine the kinetics of adsorption.

0.05 g of adsorbent was added to 50 mL HDPE bottles containing 50 mL of arsenic solution with a 10 mg/L concentration. The bottles were shaken for 0.167, 0.334, 0.5, 1, 2, 3, 6, 12, and 24 h at 25 °C. The plot of the arsenic adsorption kinetic data is shown in Fig. 4.4. The equilibrium time has been found to be 5 h.

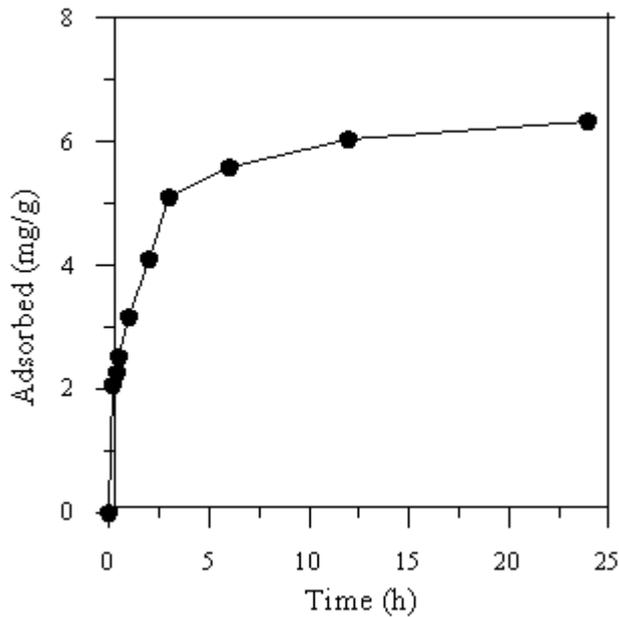


Fig. 4.4. Arsenic adsorption kinetic

To interpret the experimental data, time-dependent adsorption data have been analyzed using the linear form of the pseudo-first-order kinetic equation and pseudo-second-order kinetic equation.

The Lagergren pseudo-first-order kinetic model is expressed as (Lagergren 1898):

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (2)$$

where q_e and q_t are the amount of adsorbate adsorbed at equilibrium and at time t (mg/g), respectively, and k_1 is the rate constant of pseudo-first-order adsorption (min^{-1}). Fig. 4.5 shows the plot of the linear form of the pseudo-first-order kinetic model using the adsorption data of Fig. 4.4. The values of k_1 and q_e as well as the evaluated regression coefficients are presented in Table 4.1. Only the first portion of the adsorption kinetics yields a straight fitting line. Although the R^2 value is reasonably high ($R^2 = 0.9688$), the calculated q_e value obtained from this equation does not give a reasonably high value, too low compared with experimental q_e values. This indicates that the adsorption process does not follow the pseudo-first-order kinetic model.

The pseudo-second-order kinetic equation is given as (Ho and McKay 1999):

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (3)$$

where k_2 is the rate constant of pseudo-second-order adsorption (g/mg min). Fig. 4.6 shows the linear plot of the pseudo-second-order equation using the data from Fig. 4.4. The plot was found to be linear over the entire sorption period with high regression coefficients ($R^2 = 0.9989$), confirming the applicability of the pseudo-second-order kinetic model. The pseudo-second-order rate constant (k_2) and equilibrium capacity (q_e) determined from the slope and intercept of the plot (Fig. 4.6) are listed in Table 4.1. The theoretical q_e value was also very close to the experimental q_e value in the

case of the pseudo-second-order kinetic equation (Table 4.1). It is clear from the accuracy of the model that the adsorption of arsenic on Fe-Mn-Si is more appropriately described by the pseudo-second-order kinetic model.

Table 4.1. First- and second-order kinetic parameters

Pseudo-First-Order Kinetic			Pseudo-Second-Order Kinetic		
$k_1(\text{min}^{-1})$	$q_e(\text{mg/g})$	R^2	$k_1(\text{min}^{-1})$	$q_e(\text{mg/g})$	R^2
1.357	1.53	0.9688	0.188	6.51	0.9989

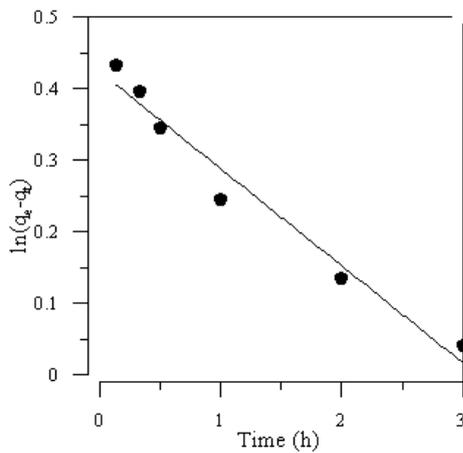


Fig. 4.5. Pseudo-first-order k

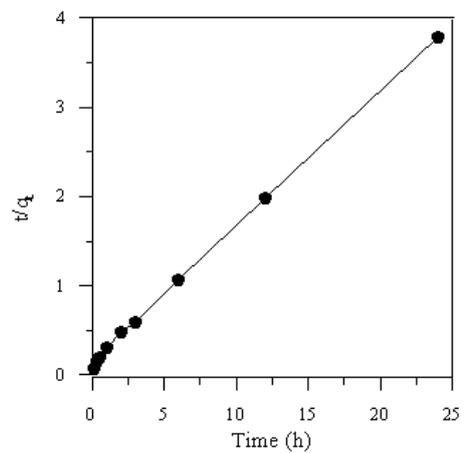


Fig. 4.6. Pseudo-second-order

4.3.3. Adsorption isotherms

To study the adsorption isotherm of the Fe-Mn-Si oxide for arsenic, 0.5 g of Fe-Mn-Si oxide was added to various 50 mL arsenic solution samples having concentration in the range of 1–100 mg/L at an initial pH of 7. Each

sample was shaken for 24 h at 25, 35, and 45 °C under constant shaking of 160 rpm. Fig. 4.7 shows the results of arsenic adsorption isotherms on Fe-Mn-Si oxide at different temperatures.

The experimental data obtained were plotted in a linear form of Langmuir (Langmuir 1918) and Freundlich (Freundlich 1906) isotherm models as shown below:

$$\frac{C_e}{q_e} = \frac{1}{bq_m} + \frac{C_e}{q_m} \quad (4)$$

$$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e \quad (5)$$

where C_e is the equilibrium concentration (mg/L); q_e , the amount adsorbed at equilibrium (mg/g); q_m , the Langmuir constant related to the maximum adsorption capacity (mg/g); and b , an energy term (L/mg), which varies as a function of surface coverage strictly due to variations in the heat of adsorption. K_f and n are the Freundlich constants related to the adsorption capacity of the adsorbent and the magnitude of the adsorption driving force, respectively. The adsorption data of arsenic on Fe-Mn-Si oxide selectively followed Langmuir and/or Freundlich isotherm models at different temperatures, as shown in Figs. 4.8 and 4.9. The calculated isotherm parameters along with correlation coefficients are given in Table 4.2.

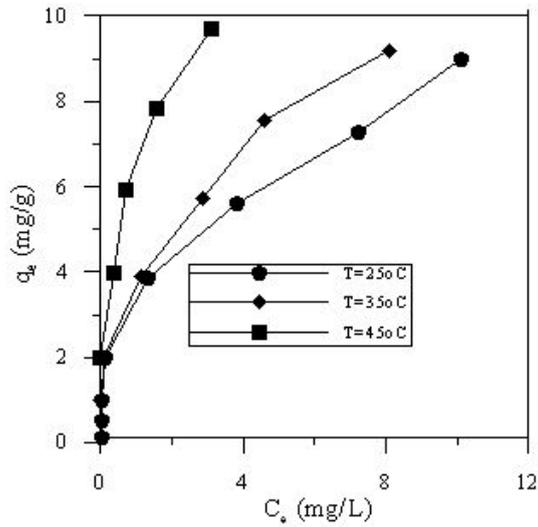


Fig. 4.7-Arsenic isotherms on Fe-Mn-Si oxide

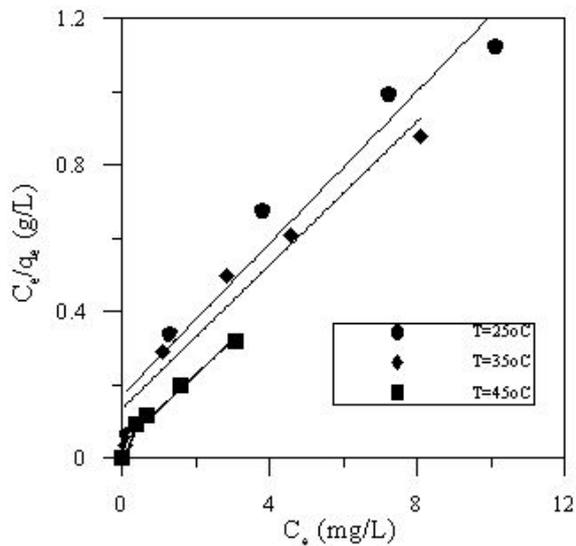


Fig. 4.8-Langmuir isotherm

Table 4.2. Langmuir, Freundlich, and D-R isotherm parameters

Langmuir isotherm		Freundlich isotherm		D-R isotherm					
T (°C)	Q_{max} (mg/g)	B	R^2	n	k_f	R^2	E (kJmol ⁻¹)	Q (mg/g)	R^2
25	9.62	0.61	0.9462	4.85	6.56	0.9163	3.32	4.86	0.9121

35	10.18	0.73	0.9431	3.0	3.80	0.9871	6.80	4.38	0.906
45	10.50	2.57	0.9601	3.11	4.33	0.9727	10.43	6.69	0.7458

It was observed that for data obtained at high temperature, the maximum adsorption capacity (q_m) of the Fe-Mn-Si oxide for arsenic increases. The maximum adsorption capacity (q_m) of the Fe-Mn-Si oxide for arsenic is found to be 9.62, 10.18, and 10.50 mg/g at 25, 35, and 45 °C, respectively. The obtained q_m values for our Fe-Mn-Si oxide material compare favorably with those obtained using other adsorbents (Table 4.3). These results suggested that the Fe-Mn-Si oxide adsorbent was effective for As(III) removal.

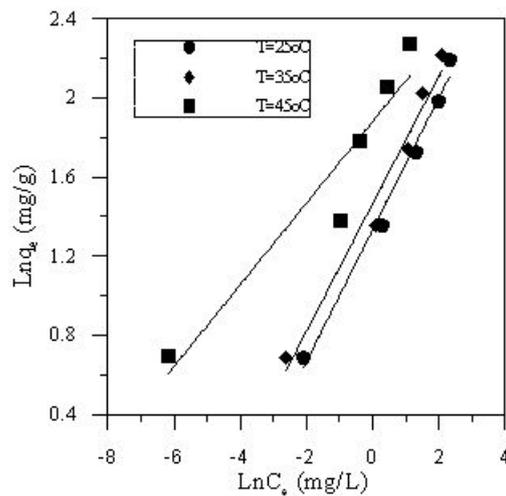


Fig. 4.9. Freundlich isotherm

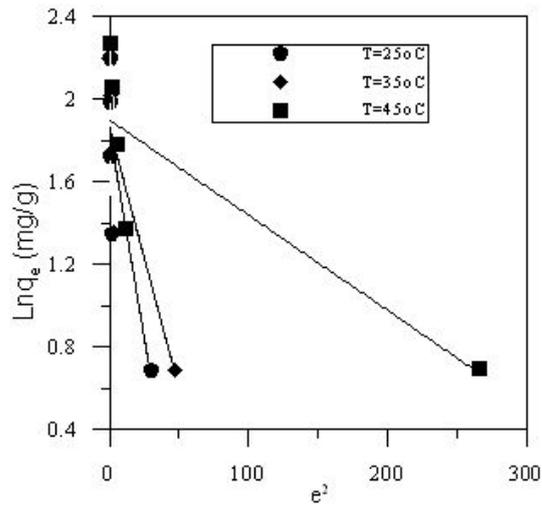


Fig. 4.10. D-R isotherm

Table 4.3. Comparison of arsenic (III) adsorption capacity with some reported adsorbents.

Adsorbent	pH	Concentration/range	Temperature	Model used to calculate adsorption capacity	q _e mg/g	References
Activated alumina	7.6	1 mg/L	25	Langmuir	0.18	(Singh and Pant 2004)
GAC	7.0		20-23	Langmuir	0.09	(Mohan and Pittman Jr 2007)
Fe (III) oxide impregnated GAC	7.0	1 mg/L	20-23	Langmuir	4.5	(Mohan and Pittman Jr 2007)
Iron-oxide-coated sand	7.6	100ug/L	22	Langmuir	0.041	(Thirunavukkarasu et al. 2003)
Iron-hydroxide-coated alumina	6.6	0.1-1.8mmol/L	25	Langmuir	7.64	(Hlavay and Polyák 2005)
Goethite	5.5	10-1000mg/L	25	Langmuir	7.5	(Ladeira and Ciminelli 2004)
Present study	7.0	1-100 mg/L	25	Langmuir	9.62	

Langmuir and Freundlich isotherms do not explain the adsorption mechanism. In order to determine the type of adsorption, the data were applied to the Dubinin–Radushkevich (D–R) isotherm (Singh and Pant 2004) and (Kundu and Gupta 2006), which can be expressed as:

$$\ln q_e = \ln q_m - k\varepsilon^2 \quad (6)$$

and

$$E = -(2k)^{-0.5} \quad (7)$$

where E is the mean free energy of adsorption; q_e , the amount of arsenic adsorbed (mg/g) at equilibrium per unit weight of adsorbent; q_m , the maximum adsorption capacity (mg/g); C_e , the equilibrium concentration of arsenic in the solution (mg/L); k , the constant related to adsorption energy ($\text{mol}^2 \text{kJ}^{-2}$); and ε , the Polanyi potential, which can be expressed as: $\varepsilon = RT \ln[(1 + (1/C_e))]$. R is the universal gas constant ($\text{kJ mol}^{-1} \text{K}^{-1}$); and T , the temperature (K). The D–R isotherm was drawn by plotting $\ln q$ against ε^2 (Fig. 4.10). The calculated isotherm parameters along with the correlation coefficients are given in Table 4.2. The values of E found in this study were 3.32, 6.80, and 10.43 kJmol^{-1} at 25, 35, and 45 °C, respectively. This indicates that the adsorption type of arsenic on Fe-Mn-Si oxide at 25 and 35 °C are physical ($E < 8 \text{ kJmol}^{-1}$) (Mahramanlioglu et al. 2002). The adsorption type of arsenic on Fe-Mn-Si oxide at 45 °C is ion exchange ($8 < E < 18 \text{ kJmol}^{-1}$) (Mahramanlioglu et al. 2002).

4.3.4. Thermodynamic parameters

From the experiments, thermodynamic parameters such as enthalpy change ΔH° , entropy change ΔS° , and Gibb's free energy (ΔG°) were calculated at different temperatures and are estimated by the following

equation (Singh and Pant 2004):

$$\Delta G^{\circ} = - RT \ln b \quad (8)$$

$$\ln b = \Delta H^{\circ} / RT \quad (9)$$

$$\Delta G^{\circ} = \Delta H^{\circ} - T \Delta S^{\circ} \quad (10)$$

where b is a Langmuir isotherm constant at temperature T , and R is an ideal gas constant (8.314 J/mol·K).

The estimated values of the thermodynamic parameters for three operating temperatures are presented in Table 4.4. The negative values of free energy (ΔG°) confirm the spontaneous nature of the arsenic adsorption process. With the increase in temperature, the free energy values decreased. This indicates that the reaction is easier at higher temperatures, which is in agreement with the result that the maximum adsorption capacity increased with temperature. The positive value of enthalpy change (ΔH°) confirms the endothermic nature of the process. The positive value of entropy change (ΔS°) suggests an increase in randomness at the solid-solution interface during the adsorption of arsenic on Fe-Mn-Si oxide.

Table 4.4. Calculated Thermodynamic parameters

T	b	ΔG°	ΔH°	ΔS°
(°C)	L/mg	kJ/mol	kJ/mol	kJ/mol
25	0.61	-26.59	56.18	0.278
35	0.73	-27.94		
45	2.57	-32.17		

4.3.5. Effect of pH on arsenic adsorption

The pH of the solution is an important factor that has a strong influence on the uptake of the adsorbate. The effect of pH on the adsorption of arsenic on the Fe-Mn-Si oxide was examined at an initial arsenic concentration of 10 mg/L and a constant adsorbent dosage of 0.5 g / 50 mL. The pH of the solution was controlled after the adsorption equilibrium to be 2.0–10.0 by adding buffer solutions. Fig. 4.11 shows the results of the adsorption equilibrium of arsenic onto the Fe-Mn-Si oxide as a function of the equilibrium pH of the solution. As shown in Fig. 10, the adsorption equilibrium of arsenic onto the Fe-Mn-Si decreased with the increase in the pH of the solution. This indicates that the amount of adsorption drops in a higher pH region because of the increase in negative-charge sites on the adsorbent surfaces. Many studies suggested that increasing pH decreased As(V) adsorption on iron-containing adsorbents. In the pH between 4 and 7, the predominant As(V) species are $\text{H}_2\text{AsO}_4^{1-}$ and HAsO_4^{2-} (Oremland and Stolz 2003), and these ions are adsorbed on Fe-Mn-Si oxide due to Coulombic interaction (Su and Puls 2001). When $\text{pH} > 9$, the dominant species of As(V) is HAsO_4^{2-} (Kanel et al. 2006), and this anion may compete with the negative site of the adsorbent surface to reduce the adsorption capability due to electrostatic repulsion (Cheng et al. 2005). The similarity of As(III) adsorption in this study indirectly suggests that the

initially added As(III) was oxidized into As(V) and then adsorbed onto Fe-Mn-Si oxide.

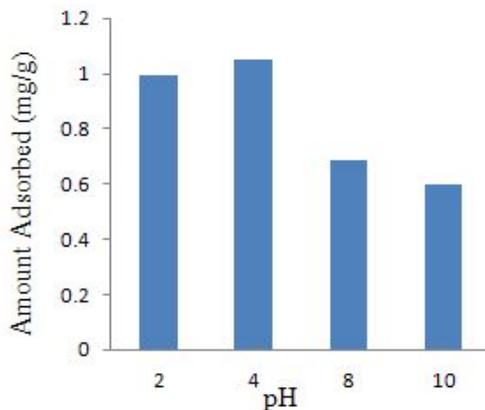


Fig. 4.11- Effect of pH

4.3.6. Desorption study

To assess the possibility of recycling the sorbent for reuse in a multiple adsorption cycle, arsenic desorption experiments for the used Fe-Mn-Si oxide were conducted using NaOH solutions of 0.01, 0.1, and 0.2 N. 0.5 g arsenic-loaded Fe-Mn-Si oxide was added to 50 mL fractions of NaOH solution and shaken for 4 h at 25 °C. It was found that arsenic desorption was 20.2, 55.2, and 73.4% with 0.01, 0.1, and 0.2N NaOH, respectively. The results (Fig. 4.12) show that arsenic-loaded Fe-Mn-Si oxide undergoes effective desorption in the presence of an alkaline-like NaOH.

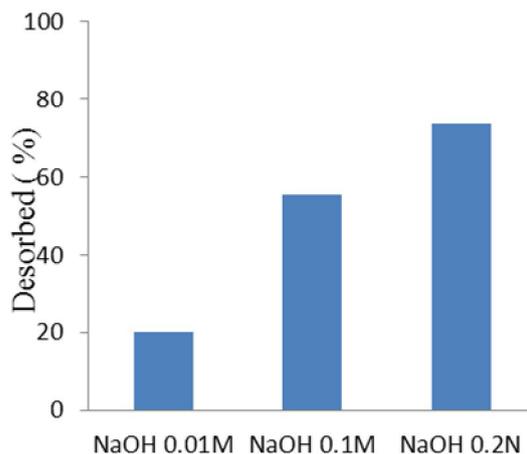


Fig. 4.12. Desorption study

4.3.7. Fixed bed column for arsenic removal

The plots of exit concentrations of arsenic as a function of lapse time or volume of water treated (breakthrough curves) for an initial As(III) concentration of 1 mg/L are shown in Fig. 4.13. The point on the breakthrough curve at which arsenic concentration reaches its maximum allowable value of 0.01 mg/L (corresponding to $C/C_0 = 0.01$) was taken as ‘breakthrough point’ and that corresponding to 90% of the influent concentration as ‘point of exhaustion’. The time corresponding to these points with respective volumes of water treated are shown in Table 4.5.

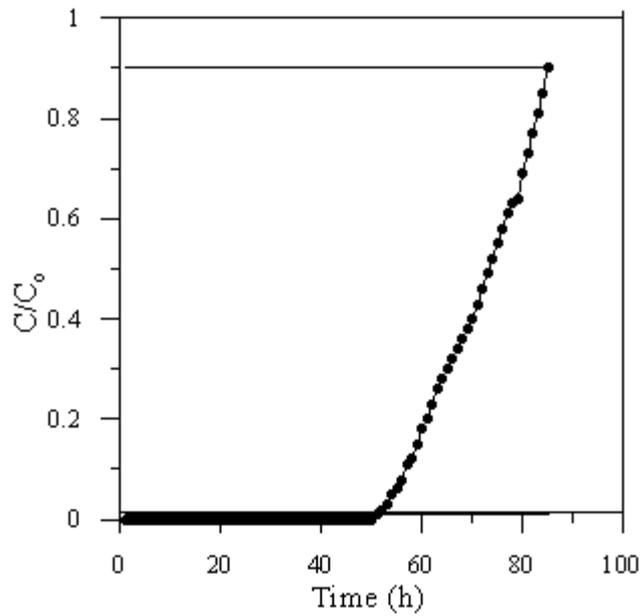


Fig. 4.13. Breakthrough curve for arsenic removal on Fe_Mn_Si oxide

Table 4.5. The total quantity of water treated in terms of bed volume before breakthrough and exhaust times

Breakthrough time (h)	Exhaust time (h)	Quantity of water treated before breakthrough (mL)	Quantity of water treated before exhaust (mL)
51	85	30,600	51,000

The time required for the exchange zone to move the length of its own height up/down the column (t_z) once it has become established is (L.D. Benefield, 1982):

$$t_z = \frac{V_s}{Q_w} \quad (1)$$

where V_s is the initial volume of As(III) spiked water treated between breakthrough and exhaustion (L) and Q_w is the influent flow rate (L/h).

The time required for the exchange zone to become established and move completely out of the bed (t_E) is:

$$t_E = \frac{V_E}{Q_w} \quad (2)$$

where V_E is the total volume of As(III) spiked water treated to the point of exhaustion (L).

The rate at which the adsorption zone is moving up and down through the bed is:

$$U_z = \frac{h_z}{t_z} = \frac{h}{t_E - t_f} \quad (3)$$

where h_z is the height of exchange zone (cm); h the total bed depth (cm); t_f is the time (h) required for the adsorption zone to form initially.

The expression for the height of the exchange zone (h_z) is:

$$h_z = \frac{h(t_z)}{t_E - t_f} \quad (4)$$

The value of t_f can be calculated as

$$t_f = (1-F)t_z \quad (5)$$

At breakthrough, the remaining fraction of the MCB (F) present in the adsorption zone still able to remove As(III) is:

$$F = \frac{S_z}{S_{\text{max}}} = \frac{\int_{V_B}^{V_E} (C_0 - C) dV}{C_0(V_E - V_B)} \quad (6)$$

where C_0 is the initial concentration of As(III) in water (mg/L); C the concentration of solute As(III) at any instant in the effluent (mg/L); V_B the total volume of As(III) spiked water treated to the point of breakthrough

(L); S_z the amount of As(III) that has been removed by the adsorption zone from breakthrough to exhaustion (mg) and S_{\max} is the amount of As(III) removed by adsorption zone if completely exhausted (mg). At breakthrough an adsorption column will not be completely saturated and will be composed of the partially exhausted zone and the totally exhausted material located above the adsorption zone. The percentage of total column bed saturated at breakthrough is:

$$\% \text{ saturation} = \frac{h + (F - 1)h_z}{h} \times 100 \quad (7)$$

The values of the important design parameters t_z , h_z , U_z and % saturation of Fe-Mn-Si oxide bed of depth of 10 cm after As(III) uptake are shown in Table 4.6.

Table 4.6. Parameters for the fixed bed MCB column

The height of the exchange zone (h_z) (cm)	The rate at which the adsorption zone is moving through the bed(U_z) (cm/h)	Bed saturated (%)	Adsorption capacity (mg/g)
6.25	0.1226	69.76	1.51

4.4. CONCLUSION

A novel adsorbent for effective arsenic removal, Fe-Mn-Si oxide, has been prepared through a coprecipitation method. The adsorbent exhibited high arsenite removal capacity. The equilibrium data fitted the Langmuir isotherm model fairly well, and the maximum adsorption capacity was found to be 9.62, 10.18, and 10.50 mg/g at 25, 35, and 45 °C, respectively. The adsorption process followed the pseudo-second-order kinetic model. Thermodynamic parameters such as ΔG° , ΔH° , and ΔS° indicate that the nature of arsenic adsorption is spontaneous and endothermic. The arsenic adsorption capacity of Fe-Mn-Si oxide is highest at low pH and sharply decreased with the increase in the pH of the solution. The used Fe-Mn-Si oxide could be regenerated using a NaOH solution; 73.4% of the adsorbed arsenic was desorbed by 0.2 N NaOH. In the column study the breakthrough time was found to be 51 h and the exhaust time was 85 h. The value of h_z , U_z and % saturation of Fe-Mn-Si was obtained as 6,75 cm, 0.1226 cm/h and 69.76%, respectively. These values could be used for the design of adsorption column. The results demonstrate that the Fe-Mn-Si oxide can be effectively used for removal of arsenic from aqueous solutions with good selectivity.

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Chapter 5. SUGGESTION WATER SUPPLY SYSTEM

5.1. Description of water supply options

There are three water supply options namely: (1) rainwater supply system; (2) groundwater supply system and (3) Dual system which rainwater is used for drinking purposes and groundwater is used for non-drinking purposes. The triple bottom line considerations, the environmental, economical, and social impacts of the systems are examined.

A brief overview of the water supply options is given as below:

5.1.1. RWH system

A RWH system generally consists of a catchment area, gutters, a filter, a settling tank and a storage tank as shown in fig. 5.1.

Catchment: The original roof is used for catchment. The roofing materials include galvanised iron and tile. For houses which do not have a good roof, we can use canvas catchment as an alternative. A smooth, clean surface with a high run-off coefficient is needed for the roofing material. The roof was made of galvanized iron sheeting that is ideal for RWH.

Gutters: Plastic and iron gutters were installed to capture rainwater running from the catchment. They were fitted on pre-installed brackets that

were customized to complement the slope of the roof in order to minimize possible overrunning and to improve catchment efficiency. The gutters were connected to the filter and settling tank using PVC pipes, and were sloped toward the pipes to facilitate good drainage.

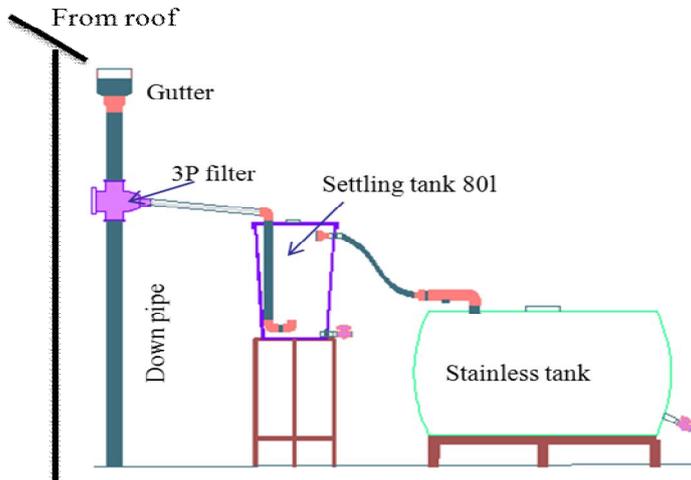


Fig. 5.1. A general RWH system

Filter: Because of lack management catchment, a filter is necessary to remove debris that gathers in the catchment area and to ensure high quality water. The filter should be simple installation and maintenance, which is an important criterion when considering suitable filters because the system will subsequently be used by laypersons that do not have strong technical knowledge.

Settling tank: Most domestic rainwater cisterns are small and subject to the problem of sediment resuspension when inflowing water falls from an

elevated inlet. Disturbance of the water surface by the inflow resuspends settled particles and thus decreases the quality of the stored water. This problem can be prevented by modifying the inlet design so that water flows ‘calmly’ into the cistern. A U-shaped inlet design, referred to as a calm inlet, reduces the potential energy of inflow and thus maintains a stable condition for the stored water and prevents the resuspension of sediment.

Storage tank: In order to get 100% reliability for a four-household, a storage tank size of 7m³ and a roof area of 300m² is recommended. The tank can be constructed from fibrocement, plastic or local stainless tank. The materials should be easy to install and effective in maintaining stored water quality.

5.1.2. Groundwater system

A groundwater system generally consists of a well, a pump, an arsenic treatment facility and a storage tank as shown in fig. 5.2. The depth of wells is about 34 – 40 meters and wells were made by manual drill equipment. Households use electric pumps to take the groundwater and treat it by an arsenic treatment facility. Fe-Mn-Si oxide adsorbent is recommended for arsenic removal. The annual total groundwater used is about 73.2 m³ per year. A fixed column has diameters of 20x20x50cm of Fe-Mn-Si oxide adsorbent is expected to treat arsenic for 1 year. The adsorbent should be replaced or cleaned by NaOH solution annual. The storage tank size of 1m³

is recommended.

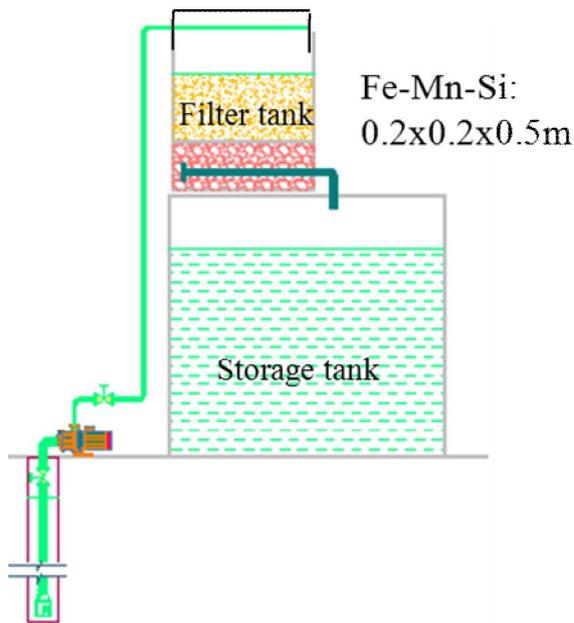


Fig. 5.2. A general groundwater system

5.1.3. Dual system

A dual system is a combination of a small RWH system and a simple groundwater system. Rainwater is used for all purposes in rainy days and only for potable purposes in dry days. Groundwater is used for non-potable purposes as a water supplement in dry days. The components of a dual system are similar with a RWH system and a groundwater system. However, the storage tank size and roof area of a dual system are smaller than a normal RWH system. In addition to, a dual system do not need to have an arsenic treatment facility. In order to get 100% reliability, a storage tank size

of 2m^3 and roof area of 100m^2 is recommended and the annual total groundwater used is expected to be 18.1m^3 .

5.2. Triple Bottom Line Consideration for Sustainable Water Supply

Of utmost importance of a water supply system is the sustainability. This approach was taken and the system addresses environmental, social and economic concerns.

5.2.1. Environmental

The RWH system has minimal environmental impact. The entire design is environmentally sustainable and self-sufficient not relying on electricity or producing unwanted emissions or waste. The rainwater harvesting system relies purely on rain water and reduces the stress on groundwater use and the surrounding underground water table. The RWH system also controls flooding problems. It requires minimal maintenance.

For the groundwater system, there is a need to maintain. The filter should be replaced or cleaned annual. The groundwater system relies on electricity. Using huge amount of groundwater is a big problem in Hanoi city. It decreases the groundwater level and makes land subsidence problems.

5.2.2. Economic

The costs of the water supply system will be significant. It is therefore recommended that the systems be implemented progressively in stages to reduce the economic strain on the households.

To assess the costs benefit of the water supply options, a Life Cycle Cost Analysis is determined and used to compare the water supply options. The equations of the systems are shown in table. 5.1

Table.5.1. Cost analyses of water supply systems.

	Initial cost	Maintenance cost
Rainwater	$C_{RWH}=C_S+C_R+C_I$	~ 0
Groundwater	$C_{GW}=C_S+ C_I+C_P+C_T+C_W$	$C_M =C_{YE} + C_{YWM}$
Dual System	$C_D=C_{RWH}+C_P+C_W$	$C_M=C_{YE} = C_E^*(D-W_S)^* 365$

C_S is the cost of the tank.

C_R is the cost of the expanded roof area

C_I includes both materials/equipment and installation costs.

C_P is the cost of the pump.

C_W is the cost of drilling well.

C_T is the cost of the filter.

C_{YE} is the yearly energy cost.

C_E is the cost of energy per cubic meter.

C_{YWM} is the cost of replacing filter material per year.

C_W is the cost of water per cubic meter.

Fig. 5.3 shows the costs of available water supply options in order to get 100% reliability. From the figure it is found that rainwater and dual system are the cheapest water supply option for long-term operation. A dual system is recommended due to the small initial cost and the feasibility on

construction.

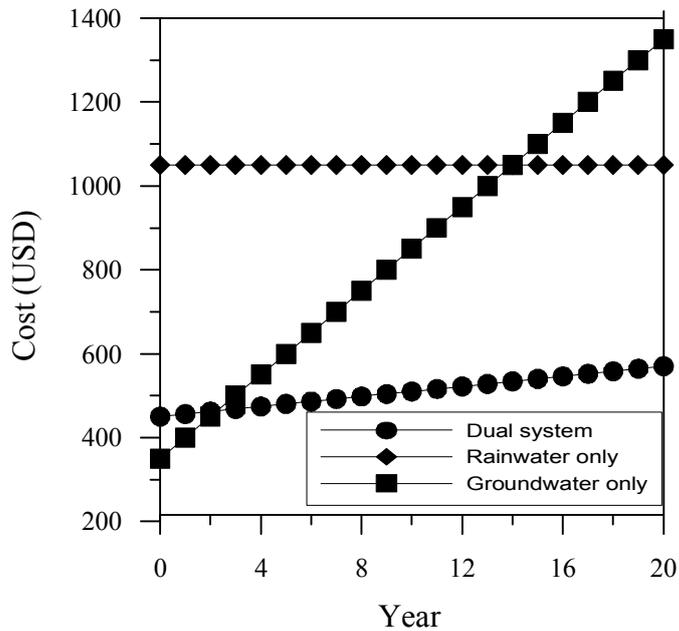


Fig. 5.3. Costs of available water supply options

5.2.3. Social

To investigate the behaviour of the residents to water sources in the village, 45 random households were interviewed about their water sources with the same questions. The questionnaire covered the use of water supplies and the reliability of water sources.

Table 5.2 shows the opinions of the local residents about water sources. Based on the results of the interviews, rainwater and groundwater are the main sources using in daily living. Rainwater is the most trusted source and

groundwater is the most un-trusted source for drinking. The reason why people do not trust groundwater is that arsenic pollution has been recognized in groundwater in here. Therefore, if the performance of the RWH systems is successful and efficient, and the local community becomes truly aware of its benefits, the concept and use of RWH will spread rapidly, even without any external forces.

Table 5.2. Interview result about the water status in Cu Khe

Water source	Purpose		Treatment		Trust (%)	
	<i>Drinking (%)</i>	<i>Washing (%)</i>	<i>Boiling (%)</i>	<i>Other (solar & none: %)</i>		
Groundwater	51	99	68	32	1	
Rainwater	49		68	32	68	
Bottled water					22	
Others					9	
Understanding about Rainwater (%)						
	Quality		For drinking		Current utilization	
	<i>Clean</i>	<i>Not clean</i>	<i>Possible</i>	<i>Impossible</i>	<i>Yes</i>	<i>No</i>
	19	81	95	5	61	39

5.6. Conclusion

There are three water supply system options namely: (1) rainwater supply system; (2) groundwater supply system and (3) Dual system which rainwater is used for drinking purposes and groundwater is used for non-drinking purposes. The triple bottom line considerations, the environmental, economical, and social impacts of the systems are examined. From the results it is clear that rainwater harvesting is a sustainable method to obtain good-quality drinking water at low cost and with little energy expenditure. A dual system, rainwater is supplied for drinking purposes and groundwater is supplied for non-drinking purposes, is recommended. For long term operation, rainwater and dual system are the cheapest water supply option. A dual system is recommended due to the small initial cost and the feasibility on construction.

Chapter 6. CONCLUSIONS

The conclusions of this study are as follow:

1. This paper investigated water supply solutions for Cukhe village – a contaminated area. The dual water supply of rainwater and groundwater is recommended. Rainwater quality is good; it can be supplied for potable purposes. Groundwater is low turbidity but too high a concentration of heavy metal (As); it can be supplied for non-potable purposes. In this paper, a novel simulation chart is developed based on rainfall variance and is then used to analyze RWH system performance. An RWH system can get optimal performance if demand is changed due to rainfall. Using rainwater for portable purposes in dry days and for all purposes in rainy days is recommended. Cost of RWH systems is analyzed. In order to get 100% reliability, an RWH system has a roof area of 100m^2 and a tank size of 2m^3 is recommended in terms of cost efficiency. For a four-household with an RWH system has a roof area of 100m^2 and a tank size of 2m^3 , it is recommended that rainwater should be supplied for only potable purposes in January-April and October-December; and should be supplied for all purposes in May-September. In addition, this study has demonstrated that rainwater harvesting can save significantly amount of water from mains top up, even in dry years in

Vietnam. These findings highlight the value that rainwater harvesting could have if fully implemented as a water management strategy in Vietnam. The design and evaluation method proposed in this paper will be useful in evaluating and comparing the performance of RWH for other areas. They can be applied to other regions using site-specific conditions.

2. A novel adsorbent for effective arsenic removal, Fe-Mn-Si oxide, has been prepared through a coprecipitation method. The adsorbent exhibited high arsenite removal capacity. The equilibrium data fitted the Langmuir isotherm model fairly well, and the maximum adsorption capacity was found to be 9.62, 10.18, and 10.50 mg/g at 25, 35, and 45 °C, respectively. The adsorption process followed the pseudo-second-order kinetic model. Thermodynamic parameters such as ΔG° , ΔH° , and ΔS° indicate that the nature of arsenic adsorption is spontaneous and endothermic. The arsenic adsorption capacity of Fe-Mn-Si oxide is highest at low pH and sharply decreased with the increase in the pH of the solution. The used Fe-Mn-Si oxide could be regenerated using a NaOH solution; 73.4% of the adsorbed arsenic was desorbed by 0.2 N NaOH. In the column study the breakthrough time was found to be 51 h and the exhaust time was 85 h. The value of h_z , U_z and % saturation of Fe-Mn-Si was obtained as 6,75 cm, 0.1226 cm/h and 69.76%, respectively. These values could be used

for the design of adsorption column. The results demonstrate that the Fe-Mn-Si oxide can be effectively used for removal of arsenic from aqueous solutions with good selectivity.

3. There are three water supply system options namely: (1) rainwater supply system; (2) groundwater supply system and (3) Dual system which rainwater is used for drinking purposes and groundwater is used for non-drinking purposes and. The triple bottom line considerations, the environmental, economical, and social impacts of the systems are examined. From the results it is clear that rainwater harvesting is a sustainable method to obtain good-quality drinking water at low cost and with little energy expenditure. A dual system, rainwater is supplied for drinking purposes and groundwater is supplied for non-drinking purposes, is recommended. For long term operation, rainwater and dual system are the cheapest water supply option. A dual system is recommended due to the small initial cost and the feasibility on construction.

Abstract국문초록

Design of Dual Water Supply System
Using Rainwater and Groundwater at
Arsenic Contaminated Area in Vietnam

빗물과 지하수를 이용한 베트남의
용수공급시스템 개발

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베트남 하노이 외곽지역에 위치한 쿠케는 상수도가 공급되지 않고, 지하수는 비소로 오염되어 있어 물부족으로 어려움을 겪고 있는 지역이다. 본 연구에서는 쿠바지역 주민들에게 지속 가능한

용수공급 시스템을 제공하기 위하여 빗물과 지하수를 이용한 용수공급 방법을 개발하였다. 빗물과 지하수는 각각 음용수와 비음용수용으로 설계되었다. 빗물이용시설 설계는 강우량 변화에 따라 빗물과 지하수 사용량을 조절함으로써 운전을 최적화하였다. 또한 음용수인 빗물의 절약 방법과 베트남 쿠케 지역의 물자급률을 평가하였다. 빗물은 음용수 기준에 적합하기 때문에 우기에는 모든 용수에 이용하고, 건기에는 음용수만으로 사용하는 것으로 용수시스템을 설계했다. 빗물이용시설의 비용을 분석한 결과, 집수면적이 100m², 저장조 용량이 2m³ 일 경우 100%의 물자급률을 달성 할 수 있으며 비용도 저렴 했다. 연간 강우량 분석 결과, 5월에서 9월을 제외한 다른 기간에는 빗물을 음용수만으로 사용하는 것이 용수공급에 효과적이었다. 지하수의 경우 Fe-Mn-Si 흡착제를 이용하여 비소를 제거하였다. Fe-Mn-Si 흡착제는 저비용의 친환경적인 재료를 공침하여 합성하였으며 회분식 실험과 컬럼실험을 통해 비소 흡착능을 평가하였다. Fe-Mn-Si 산화물은 비소를 선택적으로 흡착하는 재료로 사용할 수 있다. 결과적으로 용수공급을 위한 시스템은 (1) 빗물공급시설, (2) 지하수공급시설, (3) 빗물을 이용한 음용수 공급과 지하수를 이용한 비음용수 공급 시스템, 세 가지 경우로 나타난다. 환경적, 경제적, 사회적 영향을 평가한 결과,

빗물이용시설이 가장 비용이 저렴하고 에너지 사용량이 적으며, 음용수에 적합한 수질을 얻을 수 있다. 또한 빗물과 지하수를 이용한 이중시스템이 공학적, 사회적, 경제적 이익이 있는 것으로 분석되었다.

Keyword주제어: Rainwater 빗물; Groundwater 지하수;

Arsenic비소; Water supply 용수공급; Developing country

개발도상국; Water management 물관리

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