MALAYSIAN JOURNAL OF ANALYTICAL SCIENCES

Published by The Malaysian Analytical Sciences Society

ISSN
1394 - 2506

IDENTIFICATION OF HAZARDOUS EVENTS FOR DRINKING WATER PRODUCTION PROCESS USING MANAGED AQUIFER RECHARGE IN THE NAKDONG RIVER DELTA, KOREA

(Pengenalpastian Kejadian Berbahaya bagi Proses Pengeluaran Air Minuman Menggunakan Akuifer Terkawal Cas Semula dalam Delta Sungai Nakdong, Korea)

Sang-Il Lee and Hyon Wook Ji*

Department of Civil and Environmental Engineering,
Dongguk University, 30, Pildong-ro 1-gil, Jung-gu, Seoul, Korea

**Corresponding author: mousehw@naver.com*

Received: 24 February 2015; Accepted: 27 October 2015

Abstract

Various hazardous events can cause chemical, microbial or physical hazards to a water supply system. The World Health Organization (WHO) and some countries have introduced the hazardous event analysis for identifying potential events which may be harmful to the safety of drinking water. This study extends the application of the hazardous event analysis into drinking water production using managed aquifer recharge (MAR). MAR is a way of using an aquifer to secure water resources by storing freshwater for future use and pumping it whenever necessary. The entire drinking water production process is subjected to the analysis from the catchment area to the consumer. Hazardous event analysis incorporates site-specific data as well as common issues occurring in the process of drinking water production. The hazardous events are classified based on chemical, microbial or physical characteristics. Likelihood and severity values are assigned, resulting in quantitative risk by multiplying them. The study site is located at a coastal area in the delta of the Nakdong River, South Korea. The site has suffered from salt water intrusion and surface water pollution from the water upstream. Nine major hazardous events were identified out of total 114 events from 10 drinking water production processes. These major hazardous events will provide useful information on what to be done to secure the water quality produced by a new water supply method.

Keywords: managed aquifer recharge, hazardous event analysis, drinking water, coastal area

Abstrak

Pelbagai kejadian berbahaya boleh menyebabkan pencemaran kimia, mikrob atau fizikal kepada sistem bekalan air. Pertubuhan Kesihatan Sedunia (WHO) dan beberapa buah negara telah memperkenalkan analisa berbahaya untuk mengenalpasti kejadian yang berpotensi membahayakan keselamatan air minuman. Kajian ini meliputi penggunaan analisa berbahaya dalam pengeluaran air minuman menggunakan akuifer terkawal cas semula (MAR). MAR adalah satu cara menggunakan akuifer untuk mendapatkan sumber air dengan menyimpan air tawar untuk kegunaan masa depan dan mengepam bila-bila masa yang diperlukan. Keseluruhan proses pengeluaran air minuman adalah tertakluk kepada analisa dari kawasan tadahan kepada pengguna. Analisa berbahaya membekalkan maklumat khusus tempat serta isu – isu yang biasa berlaku dalam proses pengeluaran air minuman. Perkara – perkara berbahaya dikelaskan berdasarkan kimia, mikrob atau ciri – ciri fizikal. Kemungkinan dan nilai – nilai ekstrim yang diberikan, menyebabkan risiko kuantitatif dengan mendarabkan mereka. Tapak kajian terletak di kawasan pantai iaitu di delta Sungai Nakdong, Korea Selatan. Tapak tersebut terdedah kepada air masin dan pencemaran air permukaan dari hulu sungai. Sembilan kejadian berbahaya dikenalpasti daripada jumlah 114 yang berlaku dalam 10 proses pengeluaran air minuman. Kejadian berbahaya utama ini akan memberikan maklumat yang berguna mengenai apa yang perlu dilakukan untuk menjamin kualiti air yang dihasilkan dengan kaedah baru bekalan air.

Kata kunci: akuifer caj semula, analisas kejadian berbahaya, air minuman, kawasan pantai

Introduction

Drinking water supplies in coastal areas are exposed to salt water intrusion and pollutants derived upstream, which affects the water quality. In addition, changes in rainfall patterns in relation to climate change also negatively affect the supply of drinking water and cause water resource management issues. In this respect, managed aquifer recharge (MAR) has been introduced to overcome such problems. MAR is a method used to bank or treat water resources using aquifers [1], whereby the water is naturally infiltrated or injected into the aquifer using a pump. This study introduces a method for aquifer storage transfer and recovery (ASTR) of MAR, which entails injecting water into a storage well using a pump and then recovering it from a different well. ASTR has some advantages. First, the use of ASTR delivers a constant supply of fresh water because it uses two different wells: the injection well and the abstraction well (Figure 1). Second, it can be used in saline aquifers because the injected water forms a lens or bubble of fresh water within the saline groundwater [2 - 4]. Third, after the intake and treatment of surface water, a drinking water supply system with ASTR uses aquifers to add natural filtration before supplying water to customers (Figure 2). In comparison with general purification plants, it is able to treat polluted surface water more safely and to decrease the load experienced by purification facilities [1].

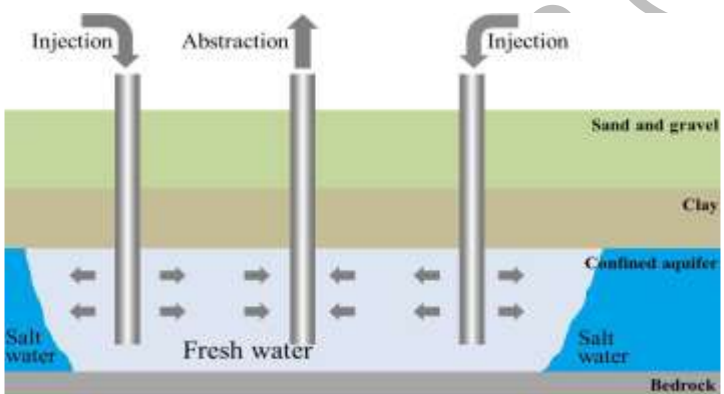

Figure 1. Schematic of ASTR in confined aquifer

Although ASTR is a more enhanced method than that used in a general drinking water supply systems, however, it remains susceptible to multifarious threats such as microbial and chemical agents that can harm public health [5] for example, suspended solid (SS), cyanobacteria, and trihalomethanes (THMs). When the drinking water supply system does not appropriately mitigate these multifarious threats, the health of the consumer can be affected because of the deterioration of the drinking water quality. These multifarious threats are hazards, which are physical, microbial and chemical agents that can bring harm to public health [5]. Hazards below the drinking water standards are harmless to humans and have no inconveniences felt when the water is ingested. However, if such hazards are exponentially increased by any triggers, they can become harmful if consumed. Such triggers are known as hazardous events, and they fail the safety of the drinking water supply system by occurring hazards [5].

Hazards and hazardous events can be determined using hazard analysis or the identification of critical control points in HACCP, which assesses hazards and establishes control systems to ensure the safety of food [6]. Using hazard analysis, or hazardous event analysis of HACCP, it is possible to prevent water quality accidents, and therefore the application to drinking water supply systems is being expanded globally.

Havelaar [7] adopted the HACCP from the food industry and applied it to drinking water supplies, and attempted to reinforce the safety of drinking water production using a hazard analysis of HACCP. The water qualities of the treatment plant in Iran were improved by applying HACCP [8, 9]. Australian drinking water guidelines [10] and the

Water Safety Plan (WSP) [5] of the World Health Organization (WHO) have also accepted HACCP in relation to drinking water production. The WSP has been accepted in economically advanced countries and has also been applied in some regions of Africa that suffer from a shortage of fresh water [11]. In relation to the above examples, it appears that ensuring the safety of drinking water is gradually being considered globally.

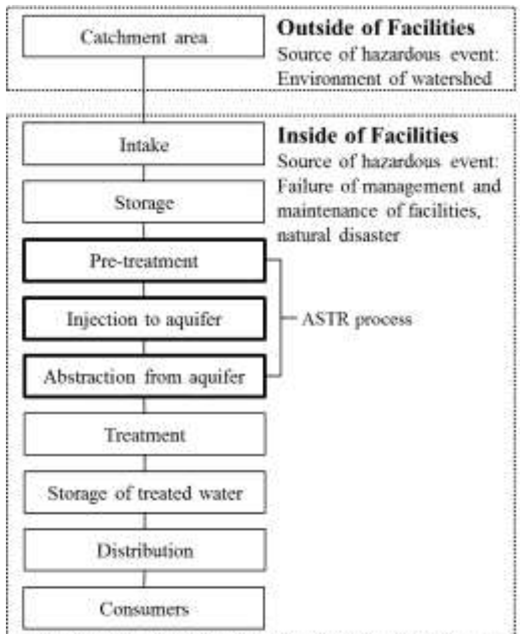

Figure 2. Drinking water supply system using ASTR

This study applied a hazardous event analysis to a drinking water supply system using ASTR, which is widely recognized as being an environment-friendly drinking water supply system [1]. Hazardous event analysis would contribute to restoring the public's lost faith in the safety of drinking water, because it can be used to prevent hazardous events through documenting potential events that could obstruct the achievement of water quality goals.

Materials and Methods

Ten processes of drinking water supply system using ASTR are analyzed (Figure 2). The use of ASTR enables to analysis of all hazardous events caused by natural and anthropogenic activities such as flood, drought, and the inappropriate maintenance and management of facilities. In this study, although various tables of analysis have previously been introduced by other studies, the analysis table of the WHO is adopted here [12].

Hazardous events can be classified as physical, microbial, or chemical [5]. A value between 1 and 5 is then assigned to the likelihood and severity of a hazardous event. The values were given by authors' judgement based on literature review, field survey, and opinion from experts. Table 1 shows the criteria used to determine likelihood and severity.

Risk is then determined by multiplying likelihood and severity and has a risk range of 1 – 25 (Eq. 1). Then the risk rating was categorized, which is classify as low (L, 1—5), medium (M, 6—9), high (H, 10–14), and very high (VH, > 15). Risk ratings of H and VH are considered to be major hazardous events that require effective management.

$$Risk = Likelihood \times Severity \quad (1)$$

Table 1. The criteria for score of likelihood and severity

	Score	Criteria[a]
Likelihood	1	Has not happened in the past and it is highly improbable that it will happen in the future
	2	Is possible and cannot be ruled out completely
	3	Is possible and under certain circumstances could happen
	4	Has occurred in the past and has the potential to happen again
	5	Has occurred in the past and could happen again
Severity	1	Insignificant or no impact
	2	Short term or localized, not health-related non-compliance or aesthetic issues
	3	Widespread aesthetic issues or long-term non-compliance not health-related
	4	Potential long-term health effects
	5	Catastrophic public health impact

[a] modified after Bartram et al. [5]

Study area

The pilot study was conducted on Samrak Park in the Nakdong River estuary, South Korea (Figure 3). This area is experiencing difficulties to the drinking water supply due to following reasons. First, the water quality of the Nakdong River has deteriorated due to the constant inflow of pollutants from upstream metropolitan cities and industrial areas [13]. Second, the ground water is saline water. Third, chemical leakage accidents have occurred in nearby industrial areas. These caused the low level of trust to the drinking water. Although upstream pollutants are contained by the Changnyeong-Haman weir (Figure 3), the public are finding it difficult to trust the quality of the drinking water produced by the water purification plant.

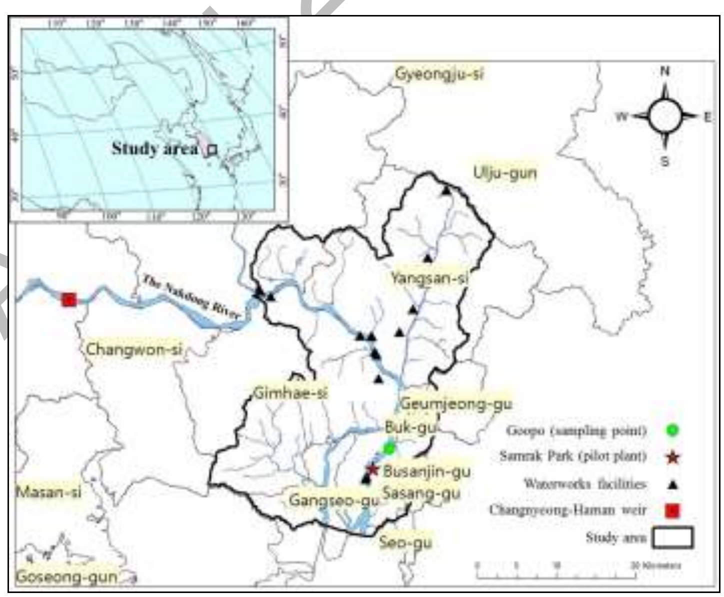

Figure 3. The downstream of Nakdong River. Study area is catchment area at the downstream of Changnyeong-Haman weir. Pilot plant is located at Samrak Park.

Physical, microbial, and chemical clogging of an injection well can occur during the ASTR operation in relation to the various substances contained within surface water. Clogging not only hinders the injection of water, but also leads to the generation of an unpleasant odor, microorganisms, and toxic materials. When clogging occurred, the wells were closed in many cases. To determine whether pre-treatment is necessary to prevent clogging, the pollutant concentration of the injected water (surface water) is checked. There can be various water quality parameters and their concentration levels to be used for checking the clogging possibility. Here we adopted Australian guidelines for ASTR.

Australian guidelines for water recycling instructs that surface water should undergo pre-treatment prior to injection if the water quality is SS > 10 mg/L or TOC > 10 mg/L [14]. Figure 4 shows the results of a water quality analysis at Goopo (Figure 3) nearby Samrak Park. Water quality was changed after building Changnyeong-Haman weir in 2011. TOC of the Nakdong River is lower than 10 mg/L every year. But, SS is higher than 10 mg/L although the weir had an effect of containing SS. Therefore, the river water needs pre-treatment before being injected.

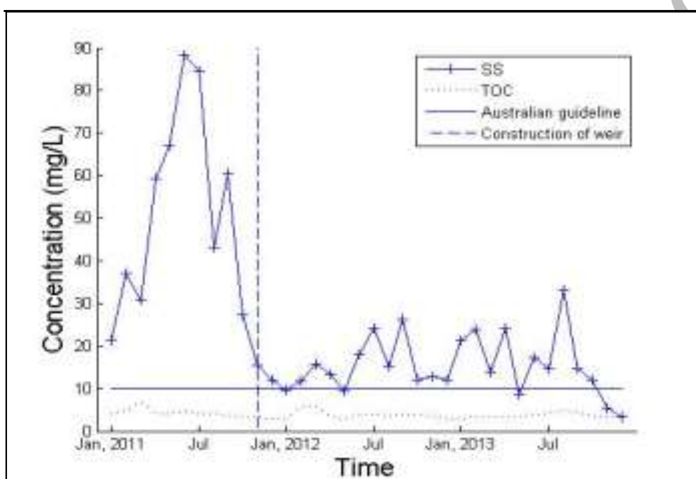

Figure 4. Water quality of the Nakdong River at Goopo (Source: www. water.nier.go.kr)

Results and Discussion

Hazardous events were considered that were unique to the study area and to the special features of ASTR such as pre-treatment, injection to aquifer, and abstraction from aquifer. In this respect, a total of 114 hazardous events were derived from ten processes of the ASTR, and a summary of hazardous events is given in Table 2.

Table 2. The number of hazardous events identified in drinking water supply system using ASTR

Process	**No.**	**Process**	**No.**
Catchment area	25	Abstraction from aquifer	8
Intake	3	Treatment	8
Storage	10	Storage of treated water	15
Pre-treatment	19	Distribution	17
Injection to aquifer	5	Consumers	4

Pollutants that directly flow into a catchment area are exposed to nature. The discharge of wastewater from industrial areas, inflow of chemical fertilizers or animal feces from agricultural and livestock industries, and the inflow of domestic sewage from metropolitan areas are all considered to be hazardous events. Pollutants accumulated on the road and railways flow into the river via surface water flow are also determined to be hazardous events. Hydraulic structures such as weirs, dams, and estuary banks are also considered to be hazardous events because they affect the water quality by interrupting the water flow. Furthermore, because the catchment area is affected by governmental policies, it is possible that an environment could be either polluted by development, or improved by environmental conservation measures or remediation policies.

A catchment area is affected by the weather conditions in addition to anthropogenic activity, and the concentration of pollutants in a river fluctuates in times of flood and drought. Other factors causing hazards are increases in temperature (promoting algal growth), and the development of stratification according to seasonal changes causing anaerobic conditions on the bottom of lakes and rivers.

When surface water is taken from a catchment area to be treated in a confined facility, the water is directly affected by the management and maintenance of aquifers and purification facilities. The malfunction of monitoring devices, the generation of disinfection by-products, power failure, and the corrosion of the equipment are considered to be potential hazardous events.

Although during the process of ASTR the water is exposed to nature within the aquifers, the number of possibly occurring hazardous events is small because the area for the ASTR process is strictly selected and limited in consideration of natural filtration. However, the inflow of outside pollutants and microorganisms through injection wells or abstraction wells, and the possibility of well-clogging are all considered hazardous events, as is the release of heavy metals from the aquifers.

It is possible that when the treated water is distributed to customers, a re-growth of microorganisms in the treated water could occur because there is still some concentration of microorganisms in treated water. The malfunction of pumps and pipe damage are also considered to be hazardous events.

Overall, 114 hazardous events were derived and Table 3 shows the nine major hazardous events that were determined to have risk ratings higher than 'High'. Possible hazards were then determined from the hazardous events. Although major hazardous events should be preferentially taken care to reduce risk, it is acknowledged that certain hazardous events cannot be handled by the maintenance facilities and need to be controlled by local or national government.

Table 3. Major hazardous events recorded during this study

process	Hazardous event	Type†	Likelihood	Severity	Risk	Risk rating‡	Hazards
Catchment area	Illegal release of waste water from restaurants and private waste water treatment plants [15]	M, C	3	5	15	H	Pathogens, nutrients, surfactants, metal, heavy metal, non-biodegradable organics, colour, odor, taste
	Discharge of waste water from factories in the upstream of the Nakdong River (e.g. Eogok Local Industrial Complex) [10, 15]	C	4	5	20	VH	Metal, heavy metal, non-biodegradable organics

Table 3 (cont'd). Major hazardous events recorded during this study

process	Hazardous event	Type†	Likelihood	Severity	Risk	Risk rating‡	Hazards
Catchment area	Release by accidents of major chemicals from industrial complex [10, 16]	C	2	5	10	H	Non-biodegradable organics
	Frequent oil leakage accidents [16]	C	2	5	10	H	NAPLs
	Land use (Effects of Busan, Kimhae and Yangsan cities) [10]	M, C, P	5	2	10	H	Pathogens, sulfur oxides, nutrients, turbidity, colour, surfactants, organic matter, oil-contaminant
	Rapid change of river water quality by flood and drought [10]	M, C	3	5	15	H	Pathogens, nutrients, turbidity, colour, algae, toxic material, odor, taste
	Year-round occurrence of eutrophication [7, 10, 17]	M, C	4	5	20	VH	Algae, toxic material, colour, odor, taste
Storage	Rapid growth of cyanobacteria by abnormal high temperature in storage tank [7, 10]	M	2	5	10	H	Algae
Storage of treated water	Regrowth of pathogens or carcinogen (THMs) by inappropriate maintenance of residual chlorine [10]	C	2	5	10	H	Pathogens, disinfection by-products

† M: Microbial, C: Chemical, P: Physical
‡ VH: Very High, H: High

Conclusion

In this study, the entire drinking water system was analyzed from source to tap. The study area was located in the Nakdong River downstream, South Korea. Various pollutants are known to enter the Nakdong River from metropolitan cities and from the industrial areas upstream. In this study, nine major hazardous events with risk ratings higher than 'High' were classified out of the 114 hazardous events derived. It is considered that the preliminary management of major hazardous events would be effective prevention in relation to water quality accidents in a drinking water supply using ASTR.

Acknowledgement

This research was supported by a grant (code 15AWMP-B066761-03) from AWMP Program funded by Ministry of Land, Infrastructure and Transport of Korean Government.

References

1. Dillon P. J. (2005). Future management of aquifer recharge. *Hydrogeology Journal*, 13 (1): 313 – 316.
2. Cederstrom, D. J. (1957) Geology and ground-water resources of the York-James Peninsula. Virginia, US Geological Survey: pp 237.
3. Bakker, M. (2010). Radial Dupuit interface flow to assess the aquifer storage and recovery potential of saltwater aquifers. *Hydrogeology Journal*, 18 (1): 107 – 115.

4. Zuurbier, K.G., Zaadnoordijk, W. J. and Stuyfzand, P. J. (2014). How multiple partially penetrating wells improve the freshwater recovery of coastal aquifer storage and recovery (ASR) systems: A field and modeling study. *Journal of Hydrology* 509 (13): 430 – 441.
5. Bartram J., Corrales L., Davison A., Deere D., Drury D., Gordon B., Howard G., Rinehold A. and Stevens M. (2009). Water Safety Plan Manual: step-by-step risk management for drinking-water suppliers. World Health Organization, Geneva.
6. Codex Alimentarius Commission. (1997). Hazard Analysis and Critical Control Point (HACCP) System and Guidelines for its Application. Annex to the Recommended International Code of Practice – General Principle of Food Hygiene, CAC/RCP 1-1969, Rev. 3.
7. Havelaar A.H. (1994). Application of HACCP to drinking water supply. *Food Control*, 5 (3): 145 – 152.
8. Khaniki G. R. J., Mahdavi M. and Mohebbi M. R. (2009). HACCP application for treatment of drinking water for Germi in Iran. *Journal of Food Agriculture and Environment*, 7 (2): 709 – 712.
9. Tavasolifar A., Bina B., Amin M. M., Ebrahimi A. and Jalali M. (2013). Implementation of hazard analysis and critical control points in the drinking water supply system. *International Journal of Environmental Health Eng*ineering, 1 (3): 1 – 7.
10. National Health and Medical Research Council – Natural Resource Management Ministerial Council, NHMRC – NRMMC (2011). Australian drinking water guidelines. EH52, Canberra.
11. World Health Organization, WHO. (2012). Water safety planning for small community water supplies. World Health Organization.
12. Deere D., Stevens M., Davison A., Helm G. and Dufour A. (2001). Water quality: guidelines, standards and health – assessment of risk and risk management for water-related infectious disease. London, World Health Organization, *IWA Publishing*: pp 257 – 288.
13. Ji H.W., Lee S.-I. and Lee S. J. (2014). Hazardous event analysis for drinking water production by managed aquifer recharge. Proceedings of the 19th IAHR-APD Congress 2014, Hanoi, Vietnam.
14. Natural Resource Management Ministerial Council – Environment Protection and Heritage Council- National Health and Medical Research Council, NRMMC-EPHC-NHMRC (2009). Australian guidelines for water recycling: managing health and environmental risks. Phase 2C: Managed Aquifer Recharge. Biotext, Canberra: pp 45 – 51.
15. Canadian Water and Wastewater Association, CWWA. (2005). Canadian Guidance Document for Managing Drinking Water Systems.
16. Lee J. K., Kim T. O. and Jung Y. J. (2013). Analysis of domestic water pollution accident and response management (in Korean). *Journal of Wetland Research*, 15 (4): 529 –534.
17. Son H. J. (2013) Long-term variations of phytoplankton biomass and water quality in the downstream of Nakdong River (in Korean). *Journal of Korea Society Environment Engineers*, 35 (4): 263 – 267.