Technology development trajectory for drinking water treatment: a comparative study between South Korea, Thailand, and Lao PDR

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ABSTRACT

This paper reports on a study to compare the technological trajectory of drinking water treatment for the past 30 years, from the 1980s to the 2010s, in South Korea, Thailand, and Lao PDR. There are significant differences in water treatment technology in the three countries, resulting from factors such as national regulations, economic conditions, and water policies. These act either as drivers or as barriers for water service development in the three countries. South Korea has introduced various new treatment technologies since the 1990s for meeting stringent regulations and for improving tap water quality and safety. Thailand and Lao PDR maintained similar treatment methods without great changes, because they focused more on quantity expansion for meeting water demand than on quality improvement. In addition, lax regulations and financial constraints acted as barriers to the development of water treatment technology in the two countries. Thailand is now trying to apply new treatment technologies, such as online monitoring, mechanical sludge collector, and dual-media filter, as water quality has grown in importance, and Lao PDR has developed new water supply systems for increasing water supply coverage. This study explored changing patterns of treatment technology in the three countries, and offered lessons for developing water treatment technology in the region.

Key words | barriers and drivers, drinking water treatment, Lao PDR and Thailand, South Korea, treatment technology trajectory, water quality regulation

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INTRODUCTION

An adequate supply of safe drinking water is one of the major prerequisites for a healthy life. Globally, over 90% of the world's population had access to a source of improved drinking water in 2015. Nearly 4.2 billion people now get water through a piped connection, while another 2.4 billion access water through other improved sources, including public taps, protected wells, and boreholes (UNICEF & WHO 2015). Despite major efforts to develop water treatment technology that is sustainable, robust, and energy efficient, many people still lack access to clean and safe fresh water in developing countries.

Usually tap water is processed and treated to meet drinking water quality standards or international guidelines. A number of methods such as coagulation, adsorption, ion exchange, chemical oxidation, and membrane process have been used for the removal of contaminants from water. However, the application of these technologies has been restricted by many factors, such as processing efficiency, energy requirement, engineering expertise, economic benefit, and infrastructure. Conventional water treatment process is the most common method for the production of drinking water throughout the world. It typically consists of several steps, including both physical processes (settling and filtration for solid separation) and chemical processes (coagulation and disinfection).

The design of water treatment plants (WTPs) depends on water quality, regulatory requirements, consumer and

environmental concerns, construction challenges, operation constraints, available treatment technologies, and economic feasibility (Hamouda *et al.* 2009; Patil & Kulkarni 2014). These various factors reflect the enormous differences of water treatment technology development in each country because they can impact either as drivers or as barriers. South Korea, for example, quickly developed its water supply system in a short period emphasizing drivers such as stringent national regulations and guidelines, consumer complaints, environmental concern, and economic condition. On the other hand, Thailand and Lao PDR were comparatively slow to develop, due to barriers such as a lack of finance, lax regulatory requirements, and a lack of concern from decision-makers and consumers.

This study aims to compare the technological trajectory of three different drinking water service systems: Korea Water Resources Corporation (K-water) in South Korea, Provincial Waterworks Authority (PWA) in Thailand, and Nam Papa Nakhone Luang (NPNL) in Lao PDR for the past 30 years (1980s–2010s). 'Technological trajectory' is defined as the paths by which innovations in a given field occur. The pathway can be expressed in terms of the characteristics of technical advances, and the concept of technological trajectory is often used to describe the dynamics of technological change. Manufacturing and service industries have already applied this concept for innovative action and service (Castellacci 2008).

The drinking water service industry also needs to be aware of the emergence and diffusion of innovative technologies to develop water treatment solutions. This study identified periodical change of treatment technology and influence factors (drivers and barriers) in the three water service providers selected. In addition, the study had the opportunity to transfer some alternative technologies from the results of a comparative study on developing existing water treatment systems in developing countries.

MATERIALS AND METHODS

Study area

The study selected three Asian countries at three different levels of economic development. The three countries may be classified according to their gross national income (GNI per capita) into three categories: high-income economies (South Korea), upper-middle-income economies (Thailand), and lower-middle-income economies (Lao PDR). These countries therefore represent the economic diversity of Asia, and the findings from the comparative study may therefore be suitable for extrapolation to other countries with similar socio-economic conditions.

To compare the transition of water treatment technology in the three countries, specific water service providers and water supply facilities were selected in the study areas. In each of the three countries, the public water supply system delivers tap water to consumers by means of both local government-owned and state-owned water service providers. This study focused on three state-owned companies: K-water in South Korea, PWA in Thailand, and NPNL in Lao PDR. State-owned companies were selected because it is relatively easier to access their water treatment facilities and more convenient to obtain data than from local government-owned providers. In addition, they account for a considerable proportion of the national drinking water supply. K-water operates a multi-regional water supply system, which is designed to provide tap water to more than two local governments, with 37 drinking WTPs in eight provinces. PWA supplies tap water to 74 out of 76 provinces in Thailand, with 233 WTPs. In this study, we selected PWA Regional Office 10 as its study area, which delivers tap water to ten provinces in lower northern and upper central Thailand. In Lao PDR, NPNL delivers tap water in Vientiane with four WTPs.

Overview of water supply system

Water supply coverage and water quantity

As presented in Table 1, about 96% of South Korea's population in 2013 had access to tap water supplied by local government waterworks and K-water (the multi-regional water supplier). This level of service was facilitated by the rapid development of the water supply system under government long-term planning, from 1980 (54.6%) to 1990 (78.4%) (MOE 2014). Around 88% of Thailand's population had access to safe water, with a higher rate in cities and towns (Pisit 2012). Tap water is currently provided by three

Table 1 | Basic information on the three water supply systems (Pisit 2012; K-water 2014a; MOE 2014; NPNL 2014)

	K-water (South Korea)	PWA (Thailand)	NPNL (Lao PDR)
Water supply rate (%)[a]	96	88	72
Water quantity (million m^3/d)[b]	4.45	4.53	0.19
Tariff (US$/$m^3$) for residence[c]	0.60	0.48	0.11
Number of WTP selected for study	37	8	4
Water source			
River	7	8	4
Reservoir	30	1[dd]	–

[a]Water supply rate is expressed as the national water supply coverage rates in 2013. However, the national supply rate is not available for Lao PDR, so it is presented as the water supply rate of Vientiane city.

[b]The water quantity is the total water volume produced from K-water, PWA, and NPNL in 2014.

[c]The tariff is calculated with increasing-block tariffs (IBT) by assuming that around 36 m^3 of tap water is consumed per household by a family of four in a month (300 L/p·d × 4 p/household × 30 d/month × 1 m^3/1,000 L). Currency equivalents (exchange rate: 1 US$ = 1,100 KRW = 33.6 THB = 8,000 LAK).

[d]There are nine water sources in PWA although there are only eight WTPs. This is because one WTP has two water sources: river in the wet season and reservoir in the dry season.

water service providers: the Metropolitan Waterworks Authority (MWA) serving Bangkok and its vicinity, PWA covering other provincial and district towns, and local authorities providing tap water to rural communities. In contrast, the water coverage rate in Vientiane, the capital of Lao PDR, was relatively low (72%) in 2013 compared to that in South Korea and Thailand. A lack of finance has contributed to delays in developing the system, but water supply coverage has increased rapidly during recent years, from 52% in 2008 to 72% in 2013, through construction of new WTPs and the expansion of existing plants.

Water tariffs

The three countries charge varying levels of water tariff due to different tariff structures and water pricing policies (Table 1). In the case of K-water, the tariff is expressed in the average water bill of South Korea, because K-water sells treated water to local governments wholesale, not to individual households. In 2013, the average tariff was 0.60 US$ per cubic meter water. PWA has an increasing-block tariff structure with four classifications: 0–10 m^3

(0.30 US$/$m^3$), 11–20 m^3 (0.47 US$/m^3), 21–30 m^3 (0.56 US$/$m^3$), and 31–50 m^3 (0.63 US$/$m^3$). This system requires the payment of a progressive tariff with increasing tap water consumption, and water tariff in PWA is 0.48 US$ per cubic meter water. In Lao PDR, the official tariff policy is to recover operation and maintenance (O&M) costs as a minimum, and to set the tariff around 3–5% of the household income. NPNL therefore has a low tariff of just 0.11 US$ per cubic meter of water.

Water treatment plant

As shown in Figure 1, K-water's WTPs have a variety of capacities, ranging from 16,000 to 500,000 m^3/d for providing treated water to remote areas. In contrast, PWA has small-scale WTPs, ranging from 5,000 to 20,000 m^3/d because tap water is provided to nearby local residents around WTPs. NPNL has medium-scale treatment plants, ranging from 20,000 to 80,000 m^3/d for supplying tap water to the citizens of Vientiane.

The number of WTPs selected for the study is 37, eight, and four for K-water, PWA, and NPNL, respectively. It is closely related to water treatment technologies' modification among the three countries. K-water has introduced a large number of technologies in the recent past. For example, in the filtration system, the filter media configuration has changed from single fine media to dual-media, single coarse media, granular activated carbon (GAC) filter, and is being replaced by membrane filtration system. Thus, the study focused on review of a large number of WTPs in K-water to conduct a comparative study at the national level. On the other hand, PWA has used the standardized water treatment process, design, and construction for the past 20–30
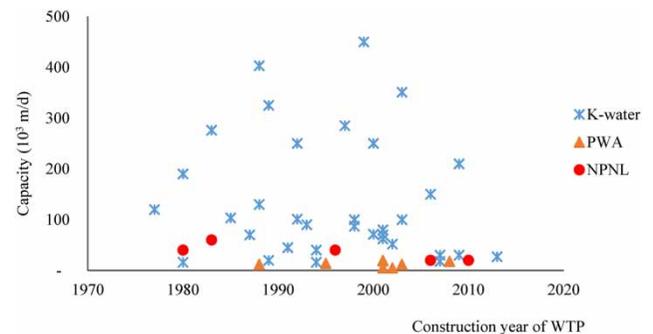
Figure 1 | WTPs selected for a comparative study in K-water, PWA, and NPNL.

years without major changes. Therefore, the study selected only eight WTPs. Considering the access to reliable and long-term technical data for Lao PDR, the study selected only the water plants (four WTPs) located in Vientiane, which is the capital and largest city of Lao PDR.

Water sources

In PWA and NPNL, raw water is drawn from major rivers, namely the Yom, the Ping, and the Nan Rivers in Thailand, and the Mekong and the Nam Ngum Rivers in Lao PDR. In South Korea, K-water extracts raw water mainly from reservoirs, specifically multipurpose dams and water supply dams. As rainfall in South Korea falls mostly during three summer months (July to September), such reservoirs are constructed to store water during the dry season, and to control flooding during the wet season. In general, river water quality is greatly affected by the hydrological factors (such as water discharge variability and floods) and human activities (such as intensive agriculture, wastewater discharge, and dredging). Especially, during flood periods, water quality usually shows marked variations due to the different origins of the water, which include surface run-off (large amounts of total suspended solids), sub-surface run-off (dissolved organic carbon and nutrients from soils), and groundwater discharge (SiO_2, Ca^{2+}, Mg^{2+}, Na^+, K^+) (Chapman 1996). Although reservoir water quality is more stable and has lower turbidity than that of river water, it is often affected by eutrophication. Algae blooms may bring about big issues in drinking water service because these organic materials generate unpleasant odor and taste in tap water.

Data collection and method

Primary data were collected by conducting field surveys in PWA operated WTPs (Nakhon Sawan, Kampheng Phet, Phichit, Phitsanulok, Sukhothai, and Tak provinces) and NPNL (Vientiane city) between 2014 and 2015, followed by a face-to-face interview with key persons responsible for the operation and management of the WTPs. Companies' annual reports, research documents, project reports, and published materials were the sources of secondary data. In the case of K-water, main data were obtained from the waterworks database of K-water, annual statistics, and case study reports.

RESULTS AND DISCUSSION

Technological trajectory of water treatment process

Conventional surface WTPs have a fairly standard sequences of processes: screening, coagulant, flocculation, sedimentation, filtration, and disinfection. The study focused on the transition of treatment technology development in K-water during the past 30 years, and compared it to that of NPNL and PWA.

Water intake facility

The intake structure is constructed at the water source for the purpose of extracting water for water treatment and water supply (Kawamura 2000). For the protection of downstream conduits, pump, and treatment works, each intake facility requires the installation of coarse and fine screens to remove suspended particulates from the water.

In K-water (Table 2), a fixed screen type was installed in the late 1980s, but it was replaced by moving screen types (a cable-operated grab cleaner or climber screen) in the mid-1990s to restore screen performance more efficiently. In the early 2000s, a debris boom was introduced to block floating trash and debris deposited around water intake facilities in the wet season. By this time, water intake facilities were focused on the water quantity aspect for raw water extraction without any interruptions. In the mid-2000s, water quality aspect became a major concern for compliance with stringent water quality regulations; thus, online monitoring instruments (pH, turbidity, conductivity, and alkalinity) were installed in water intakes. This is because the existing laboratory-based method is too slow to respond to the water treatment process according to raw water quality changes (Michael *et al.* 2011). With concern for the detection of chemical substances in raw water, however, early warning systems (EWS) have been additionally introduced to water intakes since 2010. EWS are integrated systems consisting of monitoring instrument technology with the ability to analyze and interpret data in real time

Table 2 │ Development of water treatment technology in K-water in the past 30 years

Category	1980	1990	2000	2010
Water intake				Early warning system
				Online monitoring system
			Debris boom (advanced prevention)	
		Moving screen (mechanical cleaning)		
	Fixed screen (manual cleaning)			
Rapid mixing				Advanced motionless mixing
			Pump diffuser & water champ	
		In-line blender		
	Mechanical flash mixing (high energy intensity)			
	Hydraulic mixing			
Flocculation				Low energy intensity mixer
			Automatic control system	
		Hydrofoil type mixer		
	Paddle type mixer			
	Pitched blade type mixer			
Sedimentation and sludge disposal				Sludge reuse (100%)
				Sludge dewatering (filter press)
		Sludge dewatering (belt press)		
	Mechanical sludge collector			
	Discharge to a waterway			
Filtration				Membrane system
				Granular activated carbon
			Coarse sand & water wash with air scour	
	Dual-media & water wash with surface washing			
	Fine sand & water wash with surface washing			

(Grayman *et al.* 2001; USEPA 2005). The Korean government requires the installation of biological EWS, such as daphnia (water fleas), an algae toximeter, and a fish activity monitoring system, in a facility with a given water intake amount (more than 10,000 m^3/d) according to enforcement regulations (MOE 2012).

PWA and NPNL, meanwhile, have commonly focused on raw water extraction for water intake facilities. This is because they have suffered a shortage of water due to the low water levels of water sources (rivers) in the dry season. Water intakes have used a fixed screen type, and debris (e.g., leaves, branches, and aquatic plants) has been manually removed by operators. Recently, PWA introduced an online water quality monitoring system, including temperature pH, turbidity, conductivity, dissolved oxygen (DO), and alkalinity to particular WTPs, as a demonstration project.

Rapid mixing

Rapid mixing aims to disperse coagulant species instantly and efficiently into raw water, before the flocculation, sedimentation, and filtration processes. There are several types of rapid mixing methods, such as hydraulic mixing, mechanical flash mixing, in-line static mixing (orifice mixing, motionless mixing), pump diffusion mixing, and induction mixing (water champ).

K-water has introduced various types of rapid mixing methods in the past 30 years (Table 2). Most WTPs used two mixing methods selectively, hydraulic mixing in the dry season (low turbidity) and mechanical flash mixing in the wet season (high turbidity), until the mid-1990s. However, mechanical flash mixing and hydraulic mixing with a longer retention time could not guarantee instantaneous and uniform coagulant dispersion (Kim & Lee 2006). Therefore, a new in-line mixing method (in-line blender) was introduced in the late 1990s because it could often provide more efficient rapid mixing than the conventional complete-mix type. Three WTPs installed in-line blenders, but this mixing method experienced a few problems, such as scale formation and non-uniform dispersion of coagulant chemicals. As follow-up alternatives, pump diffusion mixer and water champ were applied to 14 WTPs after the early 2000s because they were considered to have the potential to solve the main problems (noise, energy waste, and high

maintenance cost) related to the use of a mechanical mixer (Ghernaout & Boucherit 2015). With growing concern over climate change, energy use is one of the foremost issues related to drinking water supply systems. To reduce energy use for rapid mixing, advanced motionless mixing was recently proposed as an alternative method to replace the existing mechanical mixing method. The advantage of this mixer is that it does not require any external energy to be input into the system (Kawamura 2000), and it had already been introduced into four WTPs in the late 2000s.

On the other hand, PWA and NPNL have continually used a conventional static mixer and hydraulic jump mixing method for rapid mixing since the 1980s. These mixing methods can sometimes be highly efficient if a WTP has a relatively constant flow. However, the drawback to this procedure is that the degree of turbulence is a function of the plant flow rate; thus, there is no positive control over the degree of mixing (Kawamura 2000). For the optimization of the pretreatment process, rapid mixing requires a strong energy level for complete mixing with water and chemicals within a limited time. In fact, it is hard to expect this effect from the existing two mixing methods (conventional static mixing and hydraulic jump mixing) in PWA and NPNL.

Flocculation

Flocculation is a gentle mixing phase to accelerate the rate of particle collisions, causing the agglomeration of electrolytically destabilized colloidal particles into a settleable and filterable size. Optimum floc that is efficiently settled or filtered is usually formed under conditions of gradually reducing energy. Flocculation can be achieved by hydraulic methods or mechanical devices.

K-water has used mechanical types of mixers, such as the paddle type with vertical shafts or horizontal shafts and the vertical shaft with a mixing blade for flocculation. This is because mechanical flocculators have great flexibility in varying the G value (velocity gradient) according to the season. South Korea has four distinct seasons; thus, the temperature greatly varies from −6 to 22 °C (daily mean). Generally, the G value should be controlled on the basis of water temperature, namely, by increasing it in the winter season and by decreasing it in the summer season.

As presented in Table 2, the pitched blade mixer and paddle mixer were mainly used for flocculation by the middle 1990s. However, the existing pitched blade mixer was replaced by the new hydrofoil type mixer in the 2000s because of its high mixing efficiency (Tomáš & František 2011). With the application of an automated process control system in WTP, the flocculation process also employed the automatic control system for the adjustment of appropriate G values on a seasonal basis without manual control by operators. The old and deteriorated mixers are gradually being changed to hydrofoil-type mixers.

PWA and NPNL have used the hydraulic flocculation method (i.e., horizontal (round-the-end) and vertical (over-and-under) baffled channels). Hydraulic flocculation methods are simple and effective, especially if the flow is relatively constant and it is designed properly. However, they have several disadvantages, including lack of flexibility regarding mixing intensity and potential difficulty in cleaning basins. According to a feasibility study report on the Vientiane water supply development project (JICA 2004), NPNL selected the baffle-channel type for flocculation because of its low construction cost and easy O&M. Interestingly, PWA and NPNL preferred different types of baffle channels, the horizontal channel type and the vertical baffled channel type, respectively. The selection of two types is largely dependent on the flow rate and depth. Generally, horizontal flow is used for high flow rates to avoid building the plants even taller, instead making them wider. The choice of different baffle channels may be based on water service providers' (PWA, NPNL) preferences.

Sedimentation and sludge disposal

Sedimentation is the process of allowing particles in suspension in water to settle out of the suspension under the effect of gravity. Most sedimentation basins are the horizontal-flow type in rectangular and circular designs. Solid waste that has settled in the sedimentation basin should be disposed of using a cost-effective and feasible sludge treatment method.

As presented in Table 2, K-water installed mechanical sludge collectors in sedimentation basins, such as a cable-operated underwater bogie and a chain-and-flight collector. In particular, the cable-operated underwater bogie collector, accounting for 76% of total sludge collectors in K-water, has

been widely used for collecting settled solid waste due to its lower energy consumption and easy O&M. For sludge handling and appropriate disposal, a mechanical dewatering system, including gravity thickening and dewatering machines (belt press, filter press), was introduced in most water plants because of limited land space and climate conditions. The belt press was the most popular dewatering method by the early 2000s in K-water due to its relatively low cost (capital, O&M) and the minimal attention required. However, the aim of dewatering is to decrease sludge volume because of its associated disposal costs and environmental risks. The filter press was proposed as a new alternative for a high solid content of sludge, and eight WTPs were installed after the mid-2000s (K-water 2014a), although it is a batch process that requires a considerable outlay of capital and has a high operational cost. The dewatered sludge cake was usually disposed of by two methods (landfill and ocean dumping) before the enforcement regulations of new environmental law (Ministry of Maritime Affairs and Fisheries Regulations No. 330, 2006) prohibited the ocean dumping of sludge. Since 2013, K-water has reused 100% of the sludge cake generated from WTPs as cement materials (83.8%), cover materials (12.1%), planting soil (0.9%), and potting soil (0.3%) (K-water 2014b).

In PWA and NPNL, most sedimentation basins were manually cleaned periodically (once every two or three months) with low labor rates. However, the manual cleaning method has a great disadvantage in that the basin must be taken off-line when it is cleaned; consequently, this can cause an insufficient water supply by decreasing the plant capacity temporarily. PWA recently introduced mechanical sludge collectors in a few WTPs for improving operational efficiency as a demonstration project in 2010. NPNL does not have any mechanical sludge collector systems, and has discharged solid waste into natural waterways (rivers). PWA has water ponds (lagoons) for handling drained solid waste in WTPs, but the accumulated sludge of water ponds is not removed regularly by appropriate disposal methods (landfill or reuse) after dewatering.

Filtration

Filtration is a complex process for removing particulate material by high-rate granular filter media. The most

commonly used filter media are natural silica sand, crushed anthracite coal, and GAC. Backwashing is required to clean the bed when filter media increase the amount of solids retained with filtration. There are two backwash methods: upflow water wash with surface wash and upflow water wash with air scour.

K-water, PWA, and NPNL have commonly used rapid sand filter beds, but they have used different development patterns in filter media configurations and backwash methods for the past 30 years. In the case of K-water, the medium used in rapid filters was conventional fine sand (about 0.60–0.75 m deep) from the 1980s to mid-1990s. To increase the available storage capacity in the bed and decrease the rate of head-loss buildup, dual-media filters containing silica sand and anthracite (0.75–1.0 m deep) have been installed in WTPs since the mid-1980s. Since the late 1990s, there has been strong interest in single coarse sand filters (about 1.0–1.2 m deep) (Table 2). Effective backwashing is crucial to longer filtration cycles and good water quality in filtration. K-water introduced the water wash with surface wash method in the late 1990s. Twenty-six WTPs (around 70% of total plants) have used this backwashing method. Backwash with air scour was first introduced in 1994 and has been widely used as a backwashing method since 2000. For removing dissolved organic matter, filtration has been combined in a single unit using GAC since the mid-2000s. The GAC filter is usually composed of a GAC layer of 1.0–1.2 m over a silica sand layer of 0.25–0.3 m, and has been operated in three WTPs. As an application of new technology, the membrane system was introduced in drinking water treatment in the late 2000s. Three WTPs have already installed the microfiltration system (16,000 to 30,000 m^3/d) to remove solid particles on behalf of the existing filtration system.

In NPNL, the first WTP was constructed in 1963 with a fine sand medium (0.7 m deep) and water wash with surface washing. However, the second WTP introduced a single coarse sand filter (1.0 m deep) and upflow water wash with air scour in 1980. It is worth noting that NPNL applied these filter systems early: the coarse sand filter for increasing filter run-time by decreasing head loss and the filter backwash method through the combination of air and water for ensuring the best filtration performance (Chipps *et al.* 1995). NPNL installed these

systems around 15 years earlier than K-water. It was greatly influenced by the technical and financial assistance of international cooperative agencies for water supply system development. In contrast, PWA has used the conventional fine sand filter (0.6–0.7 m deep) and water wash method with surface washing. PWA recently changed from using the existing fine sand to dual-media for particular water plants for increasing the filter run time as a demonstration project.

Transition of drinking water quality regulations

The quality of drinking water is a powerful environmental determinant of health. The effective management of drinking water quality should be supported by legislative frameworks, such as drinking water quality guidelines or regulations. They are based on current published scientific research related to health effects, esthetic effects, and operational considerations. Most of all, water service providers can clearly identify how drinking water safety can be achieved and how safety should be determined from drinking water quality guidelines and regulations.

Figure 2 presents a timeline of drinking water quality standards in South Korea, Thailand, and Lao PDR. In 1963, South Korea set up the first regulation for drinking water quality at a national level with 30 parameters, mainly consisting of esthetic effects and inorganic health effects. This regulation was maintained until 1990 (for almost 30 years) without a significant change, except for one revision in 1984. With rapid industrialization and urbanization, several large water quality events occurred in succession in the early 1990s (i.e., disinfectant by-products (THMs) in 1990, phenol run-off into water sources from industrial plants in 1991, and pungent odor from water sources in 1992). These large events resulted in serious public distrust of tap water, and acted as the momentum for changing government policy from quantitative expansion to quality improvement. For example, water quality standards have been revised six times in 10 years (1990–1999), and 15 parameters have been added. The biggest advance has been made in drinking water quality since 2000. First, the turbidity criterion for treated water was strengthened to 0.5 NTU (2001) from 1 NTU. Second, treatment technique (TT), a required process intended to reduce the level
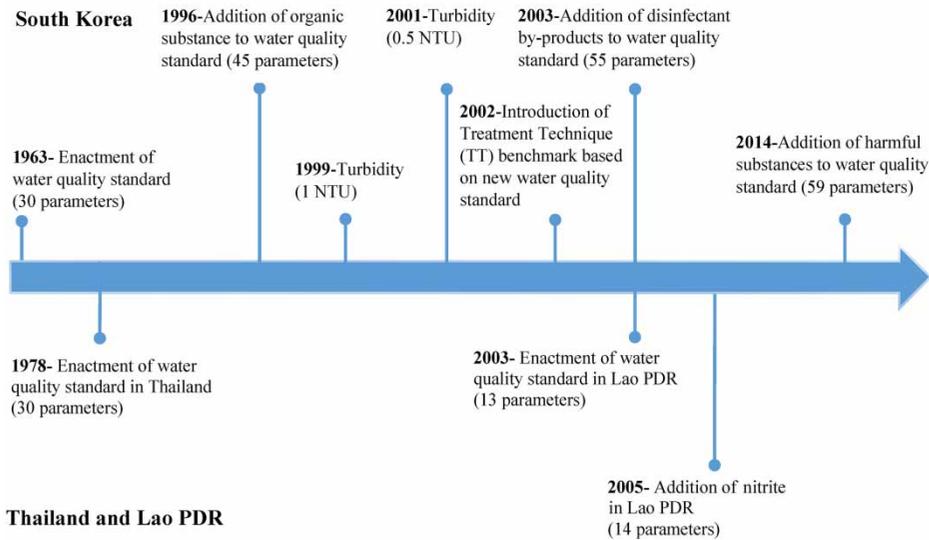
Figure 2 | Timeline of drinking water quality standards in South Korea, Thailand, and Lao PDR.

of contaminants in drinking water, was introduced in the guidelines of the treatment process in 2002 to protect public health from microorganisms such as *Cryptosporidium*, *Giardia lamblia*, and viruses. In addition, the parameters of water quality standards increased from 45 items (1999) to 59 items (2014), with a special focus on disinfection by-products and microorganism categories.

Drinking water quality standards in Thailand were established in 1978 by the Ministry of Industry, with 30 parameters. These regulations have been applied at a national level for drinking water quality without revision for almost 40 years (Figure 2). PWA developed self-implementing water quality standards (internal guidelines) in 2007, but there are no significant differences in the criteria and parameters of water quality compared with the national regulations. The turbidity, an indicator of the effectiveness of drinking water treatment processes, is less than 5 NTU.

In Lao PDR, water quality standards were established in 2003 at a national level by the Ministry of Health with 13 parameters (MOH 2004). The enactment of the regulations was relatively late in comparison with those of the other two countries, and they were revised once in 2005 to add one parameter (nitrate). The maximum allowable turbidity level is very high at less than 10 NTU, although NPNL has applied 5 NTU as a self-implementing water quality standard since 2005.

Barriers and drivers for water treatment technology development

This study identified several barriers and drivers for water treatment technology development in K-water, PWA, and NPNL.

Barriers

As presented in Table 3, lax regulation can act as a key barrier because water service providers do not feel the necessity of water treatment technology development. Moreover, the government policy of quantity-driven expansion hinders the improvement of water quality or facilities in drinking water services. Consumer desire for lower tariffs can function as a barrier for developing water supply systems because water service providers maintain an adverse balance of payments through lower water tariffs than production costs.

Developing water treatment technology requires input from many experts with a variety of skills and expertise. However, water service providers in developing countries lack personnel with knowledge of new technology trends; thus, they cannot draw up technology plans or develop a long-term strategy for water supply systems. Furthermore, they cannot embrace the latest technology and research information due to a lack of communication and interaction between water service providers.

Table 3 | Barriers for water treatment technology development

Regulations and water policy

- Lax regulations of drinking water quality standard
- Water policy of quantity-driven expansion rather than quality-driven management
- Lower water tariffs than production cost (tap water)

Knowledge and strategy

- Lack of personnel with knowledge of new technology trend
- Lack of medium- and long-term strategy on water supply system development
- Lack of information and communication between water service providers

Concern of customers and decision-makers

- Low concern of customers for water service
- Low concern of decision-makers for water supply system development
- Restricted or passive open water supply system information

Finance

- Lack of economic resources for investment in water supply system
- Low investment priority of water infrastructure facilities

Table 4 | Drivers for water treatment technology development

Compliance with regulations and guidelines with requirements

- Strict water quality standards
- Introduction of TT for safe water from pathogen
- Establishment of self-implementing water quality standards

Customer requirement/satisfaction

- Customer complaints and public distrust of tap water
- Open information on drinking water treatment

Competition

- The competition between water service providers
- Evaluation for waterworks O&M among WTPs

Employee awareness and training

- Regular training program
- Qualification system for WTP's operator

Assistance of governments and international cooperation agencies

- Support of the government budget when advanced treatment technology is introduced
- Financial support and technical assistance from international cooperation agencies

The low levels of concern of customers and decision-makers may inhibit water service development. For example, PWA (in ten provinces) received only 9.2 complaints from customers per million cubic meter of tap water supplied in 2013, but South Korea (in eight provinces) received 106.7 complaints (MOE 2014). The number of PWA's complaints was a slightly lower than expected. Sometimes, customer complaints can help water service providers to address problems before they worsen.

The water service industry comprises public infrastructure facilities that require considerable financial resources for construction and maintenance. A lack of economic resources (finance) can hinder water supply system development in developing countries. In addition, water infrastructure facilities are usually given a very low priority compared with other infrastructure facilities such as electricity, roads, railways, and information and communication.

Drivers

Some of the barriers identified also serve as drivers (Table 4). For example, stringent regulations and guidelines have acted as a powerful impetus for the rapid development of water treatment technology. Water service providers have made an effort to keep up with regulations through the introduction of new technologies as well as the establishment of strong self-implementing standards.

Customer requirements and satisfaction regarding tap water act as momentum for water service development. Water service providers in South Korea received numerous customer complaints and public distrust of tap water due to significant water quality issues in the 1990s. However, this contributed to a change in government policies on public water services, from quantity expansion to quality management. K-water actively divulged general information on tap water services to customers through the Internet, newspapers, and consumer confidence reports, and promptly responded to consumer complaints or requirements for customer satisfaction.

The competition between water service providers can serve as a catalyst for the development of treatment technology. K-water and Seoul metropolitan city are competing to provide a leading water service in South Korea, for example; thus, they introduced membrane systems for drinking water treatment around the same time (the late 2000s to early 2010s). PWA and MWA in Thailand, two state-owned

companies, have also engaged in invisible competition, although they have different service areas. This competition can increase the concern of decision-makers, motivating them to establish medium- and long-term plans (strategies) for upgrading water supply systems.

Regular training programs are an important alternative for building personnel capacity because operators play a crucial role in producing better water. K-water has a compulsory education system in which all employees have to attend job training more than once annually. In addition, the Korean government has required operators to obtain certification for water treatment operation and management according to regulation (the Water Supply and Waterworks Installation Act) since 2007. Sometimes, financial support and technical assistance from the government or international cooperation agencies have greatly contributed to public water services development.

Opportunity to transfer alternative technologies

The study had the opportunity to transfer applicable technologies for developing existing water service systems through comparative research.

Water intakes are an important means of observing the best available water quality as well as for delivering an adequate quantity of water. Online monitoring systems may have clear and multiple benefits for water intake facilities (Van der Gaag & Volz 2008) because detecting water quality in real time is the optimal way to ensure an appropriate and timely response (Michael *et al.* 2011). In addition, water quality monitoring instruments can profile and collect baseline data for gaining a better understanding of source water characteristics. Therefore, PWA and NPNL need to introduce online water quality monitoring systems as EWSs for water intakes.

The purpose of rapid mixing is to provide uniform dispersion of coagulant chemicals throughout the influent water. However, existing mixing methods such as conventional static mixing and hydraulic jump mixing, cannot be expected to achieve sufficient energy levels for complete mixing. The advanced motionless mixing method can be an attractive alternative for improving conventional static mixing in PWA and NPNL because it can achieve similar and sometimes better performance at a lower cost than a conventional agitator (Thakuri *et al.* 2003). Additionally, it

typically involves no energy consumption and few maintenance requirements as it has no moving parts.

PWA and NPNL have manually removed solid waste that has settled in sedimentation basins due to the low cost of labor, but they have commonly experienced difficulty in supplying treated water (due to a lack of capacity) whenever the sedimentation basins are cleaned. The mechanical sludge collection system is suitable for larger plants to achieve continuous and complete sludge removal. In particular, NPNL has relatively bigger capacity ($2,577 \text{ m}^3/$ basin) sedimentation basins compared with PWA; thus, NPNL needs to introduce a sludge collector system aggressively, considering O&M aspects.

Appropriate sludge disposal is an important environmental issue in drinking water service systems because it may seriously affect the aquatic habitat due to aluminum toxicity. NPNL directly discharges solid waste into natural waterways without appropriate solid waste handling and disposal because Lao PDR does not have specific regulations on solid waste disposal as yet. Some WTPs of PWA also discharge solid waste into water sources because they do not have appropriate sludge treatment facilities. Sludge lagoon drying beds have been proposed as the simplest and most cost-effective method in regions (e.g., Thailand and Lao PDR) with hot weather.

Dual-media filters can be a good alternative for improving the filtration cycle of existing filters (convention fine sand) in PWA. According to K-water's case study (Figure 3), the filter run time of dual-media filters increased by around 50% compared with that of conventional fine sand filters. Other research (Zouboulisa *et al.* 2007) reported that the dual-media filter produced much more filtered water (over 10%) than the fine sand bed through longer filtration cycles, although the water quality was the same (high quality). This is because the dual-media filter can function as a progressive sieve, which can trap the larger solids within the coarser (top) anthracite layer, whereas the smaller particles are trapped deeper within the (bottom) sand layer (Weber 1972; Zouboulisa *et al.* 2007). It can also be expected that the filter media can be changed easily from the existing fine sand to dual-media because they have a similar filter depth (around 0.6–0.7 m deep).

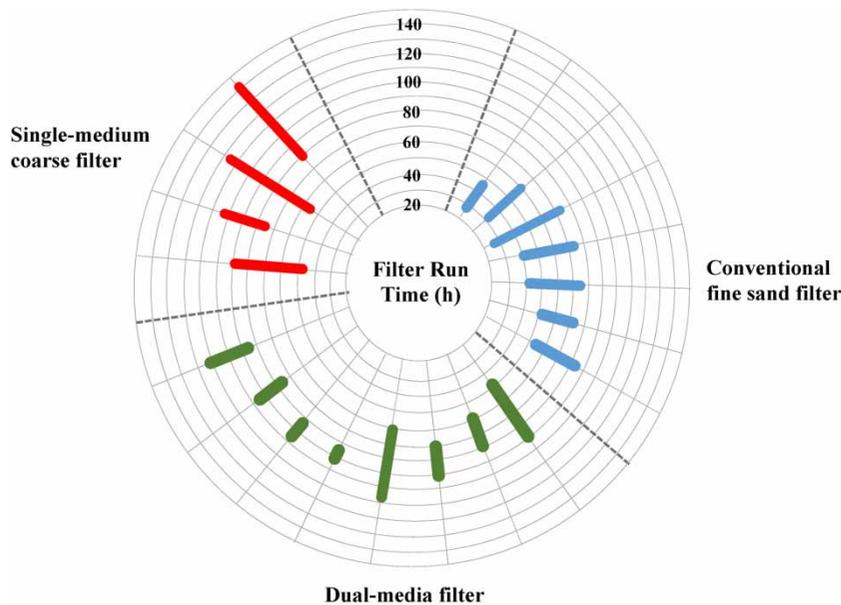PWA and NPNL need to strengthen their self-implementing standards through benchmarking the water

Figure 3 | Comparison of filter run time in K-water's 19 WTPs with three kinds of filter media configuration (2013).

quality guidelines of developed countries. Many countries (Australia, Canada, South Korea, and the USA), for example, require that filtered water should not exceed 1.0 NTU at any time (USEPA 2006; HC 2010; NHMRC 2011; NEIR 2013) because high turbidity can impact disinfection efficiency by shielding microorganisms. K-water has stronger self-implementing turbidity criterion (0.1 NTU) for treated water than the national standard (0.5 NTU).

Competition can motivate water service providers to create a superior service for their customers and highly effective operation for themselves. According to research (Lemos *et al.* 2003), this has several advantages, such as increasing innovation, efficiency, and quality (process and output) and improving customer responsiveness. For example, K-water has evaluated the operation and management of its waterworks to encourage water service development every year among its waterworks branch offices. If PWA and NPNL introduce similar evaluation systems, they can expect stronger motivation to develop water treatment technology. In addition, this is also expected to increase the awareness of decision-makers, and to encourage the sharing of useful information (technology or expertise) among staff members.

Human resource capacity building is very important for achieving water treatment development. Employee training can enable employees to become more efficient and productive workers because trained employees are also more confident in their performance and decision-making skills. In addition, employees who receive regular training are more likely to accept changes and come up with new ideas (Yamoah 2014). It has been suggested that PWA and NPNL training programs should be conducted on a regular basis for human resources capacity building and increasing water service performance.

CONCLUSION

This study compared the development of water treatment technology and water quality standards for the past 30 years in K-water, PWA, and NPNL. In addition, the study identified the main barriers and drivers for water supply system development.

Among the three countries studied, only K-water in South Korea showed a distinct trend of water treatment technology development, such as quantity expansion (the 1980s–1990s), quality improvement (the 2000s), and energy efficiency and environmental protection (the 2010s) through the active introduction of new technologies and establishment of strict self-implementing regulations. NPNL and PWA did not show any significant differences between the 1990s and 2000s. Most WTPs used a hydraulic

process and manual operation system for low operation costs. To develop water treatment technology, PWA and NPNL need to consider several alternatives, such as the advanced motionless mixer, online monitoring system, sludge dewatering and disposal method, and stringent self-implementing regulations. Most of all, PWA urgently needs to replace its existing fine sand filter with dual-media filter for longer filter run time, and it is suggested that NPNL introduce a mechanical sludge collector for operational efficiency of sedimentation basins.

From the results of the countries studied, it can be inferred that one of the main drivers of water technology development has been the 'compliance with strict regulations' followed by other drivers, such as customer requirements and competition, as well as increasing the awareness of employees through various training programs. Lax regulations, limited knowledge and strategies, and financial constraints, on the other hand, were found to inhibit water supply system development. This study found that the best way to develop the water supply system is to benchmark advanced treatment technologies.

Highlights of this study were as follows:

1. Conducted the comparative study of drinking water treatment systems in Lao PDR, Thailand, and South Korea.
2. Developed a technological trajectory timeline of water treatment for the last 30 years (1980s–2010s).
3. Explained barriers and drivers for treatment technology development.
4. Suggested applicable alternatives for technology transfer in developing countries.

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