Institut für Nutzpflanzenwissenschaften und Ressourcenschutz (INRES)

Lehr-und Forschungsbereich Pflanzenernährung

Der Rheinischen Friedrich-Wilhelms-Universität zu Bonn

Assessment of health-related risks associated with domestic water uses in the Mekong Delta of Vietnam

Inaugural – Dissertation

Zur

Erlangung des Grades

Doktor der Agrarwissenschaften

(Dr. agr.)

der

Hohen Landwirtschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität

zu Bonn

Vorgelegt am 22.09.2014

von

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Tag der mündlichen Prüfung: 22.09.2014

Erscheinungsjahr: 2014

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Acknowledgements

Firstly, I would like to thank my supervisors Dr. Fabrice Renaud and Dr. Zita Sebesvari for their guidance, support and the opportunity they gave me to do this PhD project. I am also grateful to Prof. Dr. Mathias Becker for his supervision especially regarding the writing of peer-reviewed articles and this thesis.

My thanks to BMBF (*Bundesministerium für Bildung und Forschung* - The Federal Ministry of Education and Research) for providing final support within the WISDOM project. This thesis could not have been written without their funding.

I also thank the INRES Institute, within particular Dr. Ute Arnold, who helped me in the preparing phase of my study by supplying laboratory equipment, by the presentation of analyses techniques and giving other practical advices. I am also grateful to Dr. Andrea Rechenburg from the Institute of Hygiene and Public Health of the University of Bonn, for her practical advice regarding the selection and analyses of microbial indicator bacteria in water sources in the Mekong Delta. I would also like to thank Dr. Beate Pfistner from the Institute for applied Mathematics of the University of Bonn for her statistical support during this study.

I would like to thank the Department of Natural Resources and Environment (DONRE) of Can Tho, especially Ms. Sen and Mr. Tam, who allowed me to work in their laboratory unit and gave their support throughout my field work in Vietnam. Without this cooperation it would have been difficult to determine concentrations/levels of nutrient, salt and other important water quality parameters in the collected water samples.. Special thanks to the AKIZ project, in particular Mr. Ferdinand Friedrichs and Mr. René Heinrich, for their support and their allowance to let me work in their laboratory facility. Without their cooperation it would have been difficult to analyze water samples for metals and microbial pollutants.

Many thanks to Ms. Ngoc and Ms. Yen who I met via a contact in the Netherlands. I am very grateful for their help regarding housing and finding a research assistant in Can Tho which really helped to organize my private life and work in the Mekong Delta. I would especially like to thank Mr. Nhan, who was my research assistant for 14 months. It was due to his dedicated work spirit that I was able to collect hundreds of water samples and household interviews. These three persons and their kind families have made the stay for me and my wife in Vietnam pleasant and memorable. We will never forget the enjoyable dinners and invitations with their families, even during the Vietnamese New Year.

Finally, huge thanks to my wife Priskila who supported me throughout my entire PhD project and my parents with whom I shared my troubles and problems over the years undertaking this thesis. Their moral support was the key factor to successfully complete my PhD program.

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List of Abbreviations

Al	Aluminum
As	Arsenic
ASS	Acid Sulfate Soils
Ba	Barium
Cd	Cadmium
CFU	Colony Forming Unit
Cl	Chloride
COD	Chemical Oxygen Demand
Cr	Chromium
Cu	Copper
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DONRE	Department of Natural Resources and Environment (In Vietnam)
EC	Electrical Conductivity
E. coli	Escherichia coli
EU	European Union
Fe	Iron
FTU	Formazin Turbidity Units
GGS	Gaussian Geostatistical Simulation
GIS	Geographic Information System
GW	Groundwater
Hg	Mercury
HH	Household
HHR	Household Harvested Rainwater
MD	Mekong Delta
MDG	Millennium Development Goal
Mg	Magnesium

Mn	Manganese
N_2	Nitrogen gas
N_2O	Nitrous oxide
Na	Sodium
NH_4	Ammonium
Ni	Nickel
NO_2	Nitrite
NO_3	Nitrate
o-PO_4	Ortho-phosphate
Pb	Lead
PCA	Principal Component Analysis
PE	Polyethylene
POU	Point-of-Use
PW	Piped-water
RW	Rain water
SO_4	Sulfate
SW	Surface water
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
Total N	Total Nitrogen
VG	Vietnamese government
VND	Vietnamese Dong (currency)
WHO	World Health Organisation
Zn	Zinc

Abstract

The Mekong Delta in the South of Vietnam is characterized by its intensive agricultural production. Access to safe and clean water supplies for drinking and domestic services is poor, especially for rural communities. Water-related diseases are prevalent and may lead to loss of income to families, threat economical development in the region and may even lead to increased morbidity. This study aims at defining health-related risks associated with the use of different drinking/domestic water sources and providing advices to authorities in Vietnam on how to reduce incidences of water-related diseases. The quality of 248 surface-, 116 ground-, 78 household harvested rain- and 41 piped-water samples were assessed for salinity, nutrients, metal(loid)s and microbial indicator bacteria. In addition, 40 household-stored surface- and groundwater and 10 bottled water samples were collected for reference data. Water quality maps were developed to identify hot-spot areas of pollution for surface- and groundwater. Furthermore, 532 household interviews were conducted in the Can Tho, Hau Giang and Soc Trang provinces during November 2011 – September 2012 to assess people’s use as well as perception and handling practices towards these water sources.

All investigated water sources were contaminated at levels that may pose risks to human health. Surface water in lower order canals, which are intensively used by rural communities for drinking and domestic purposes, is heavily polluted by (untreated) waste water, soil leaching and agrichemicals, leading to elevated concentrations of nutrients, metals and pathogens. In coastal areas, sea water intrusion render the surface water saline and hence unsuited for domestic or agricultural uses. Groundwater is particularly contaminated with nutrients and metals, including manganese and arsenic, and occasionally with pathogens. Due to intense over-exploitation of groundwater sources for drinking water supply and irrigation, many groundwater bodies have become saline and unsuitable for drinking. Groundwater must in future be used sparingly to avoid a further decline in its quality. The rainwater harvested by household contains elevated concentrations of pathogens due to unhygienic handling and storage practices. Also lead (Pb) was detected in harvested rainwater originating most probably from gutter systems. The quality of piped-water varied considerably between investigated stations. Especially in remote rural areas, supply stations often provide water of insufficient quality. Consequently, many households prefer resorting to alternative water sources for drinking and domestic uses, leading to poor maintenance and even the abandonment of supply stations. The quality of bottled water requires more detailed investigations as hundreds of brands of bottled water are currently marketed to communities in the Mekong Delta. While poor water quality is widely recognized, most inhabitants of the Mekong Delta are not truly aware of the risks associated with its use and consumption. In general, people perceive water as clean and safe for use when physical conditions like smell, color, taste and odor are positively judged. As a result, perceived clean water sources are generally not treated via i.e. alum and/or disinfected prior to consumption although it may be severely contaminated and pose a risk to human health. Particularly the household harvested rainwater is generally not treated or disinfected and entails the highest health-related risks from all investigated water sources as it is frequently contaminated with *E. coli* and other coliform bacteria. Despite being generally treated with alum (Al-chloride), surface- and groundwater contain the highest concentrations of metal(loid)s, potentially causing severe health-related risks. Moreover, the alum treatment does not effectively remove arsenic and contaminated surface- and/or groundwater may be unsafe to drink even when people apply treatment.

The development of piped-water supply station is seen, by (inter)national organizations and governments, as the main solution to provide access to safe and clean water. However, the predominant rural populations of the Mekong Delta have limited access to piped-water supply. Therefore, the use of harvested rainwater during the wet season and in some instances of ground- and/or surface water during the dry season may be recommended to rural communities, provided that the users are aware of associated health-risks and are educated in applying appropriate treatment prior to consumption. Such treatments may comprise disinfection of surface and rain water and water filtration by sand and stone filters to reduce metal concentrations in groundwater.

Zusammenfassung

Das Mekong-Delta im Süden Vietnams ist durch intensive landwirtschaftliche Produktion geprägt. Insbesondere in den ländlichen Bereichen des Deltas ist der Zugang zu sicherem und sauberem Trink- und Brauchwasser unzureichend. Wasserbürtige Krankheiten sind weit verbreitet und können zu Einkommensausfällen, zu einer Beeinträchtigung der wirtschaftlichen Entwicklung der Region bis hin zu einer erhöhten Morbidität führen. Ziel dieser Studie ist es, die gesundheitlichen Risiken, die mit der Nutzung unterschiedlicher Trink- und Brauchwasserquellen assoziiert sind, zu charakterisieren und Empfehlungen zur Reduzierung wasserbürtiger Krankheitsfälle für die lokalen Behörden in Vietnam zu entwickeln.

Die Wasserqualität wurde für 248 Oberflächenwasserproben, 116 Grundwasserproben, 78 Regenwasserproben (für Regenwasser, das in den Haushalten aufgefangen und gespeichert wurde), sowie 41 Leitungswasserproben anhand des Gehalts an Salz, Nährstoffen, Metall(oid)en und mikrobiellen Indikatorbakterien beurteilt. Zum Vergleich wurden zusätzlich 40 Proben von Oberflächen- und Grundwasser untersucht, welches von Haushalten über längere gelagert wurden, sowie 10 Proben abgefüllten (Mineral)wassers.Darüber hinaus wurden 40 Oberflächen- und Grundwasserproben untersucht, die vorab in den Haushalten gelagert wurden. Zudem wurde abgefülltes Mineralwasser (10 Proben) für Referenzzwecke untersucht. Basierend auf den Analysewerten wurden Wasserqualitätskarten erstellt, um Hot Spots zu identifizieren, d.h. Gebiete, in denen das Oberflächen- und Grundwasser besonders belastet ist. Zusätzlich wurden im Zeitraum von November 2011 bis September 2012 Befragungen in 532 Haushalten in den Provinzen Can Tho, Hau Giang und Soc Trang durchgeführt. Darin wurde die Nutzung der unterschiedlichen Wasserbezugsquellen, die Wahrnehmung der Wasserqualität sowie angewandte Maßnahmen zur Wasserlagerung und -aufbereitung erfasst.

Alle untersuchten Wasserquellen waren zu dem Maße belastet, dass ein Gesundheitsrisiko bestehen könnte. Das Oberflächenwasser in den kleineren, untergeordneten Kanälen wird von der ländlichen Bevölkerung häufig als Trink- und Brauchwasser genutzt. Es ist stark durch das Einleiten von (unbehandeltem) Abwasser und Agrochemikalien aber auch durch die Auswaschung von Schadstoffen aus dem Boden belastet, sodass erhöhte Konzentrationen an Nährstoffen, Metallen und Krankheitserregern vorliegen. In den Küstengebieten erhöht Meerwasserintrusion die Salinität des Oberflächen- und Grundwassers, wodurch es für die häusliche und landwirtschaftliche Nutzung unbrauchbar wird. Grundwasser ist vor allem mit Nährstoffen und Metallen (einschließlich Mangan und Arsen) kontaminiert, gelegentlich liegt auch eine Belastung mit Krankheitserregern vor. Durch die intensive Übernutzung der Grundwasserressourcen für die Trinkwasserversorgung und Bewässerung ist Grundwasser heute durch Versalzung in vielen Bereichen zum Trinken ungeeignet. Grundwasser muss in Zukunft sparsam verwendet werden, um den weiteren Rückgang der Wasserqualität zu vermeiden.

In den Haushalten aufgefangenes Regenwasser weist erhöhte Konzentrationen an Krankheitserregern auf, was auf eine unhygenische Handhabung und Speicherung des Regenwassers zurückzuführen ist. Auch Blei (Pb) wurde in gesammeltem Regenwasser nachgewiesen. Diese Belastung geht vermutlich von bleihaltigen Regen- und Dachrinnen aus. Die Qualität des Leitungswassers variiert erheblich und war insbesondere in abgelegenen ländlichen Gebieten unzureichend. Daher bevorzugen viele Haushalte Trink- und Brauchwasser aus alternativen Quellen, was zu einer schlechten Wartung und gelegentlich sogar zur Aufgabe der Wasserversorgungsstationen führt . Die Beurteilung der Qualität von abgefülltem Wasser erfordert weitere, detaillierte Untersuchungen, da es Hunderte von Herstellern gibt, die derzeit die Gemeinden im Mekong-Delta beliefern.

Obwohl die schlechte Qualität des zur Verfügung stehenden Wassers bekannt ist, sind den meisten Bewohnern des Mekong-Deltas die Risiken, die mit der Verwendung des Wassers verbunden sind, nicht wirklich bewusst. Im Allgemeinen nehmen die Bewohner an, dass das Wasser sauber und sicher ist, sofern Geruch, Farbe und Geschmack positiv beurteilt werden können. Wasser, das auf diese Art als sauber wahrgenommen wird, wird in der Regel nicht behandelt (z. B. mit Alaun) oder desinfiziert, obwohl es stark kontaminiert sein und eine Gefahr für die Gesundheit darstellen könnte. Insbesondere aufgefangenes Regenwasser wird selten behandelt oder desinfiziert und birgt somit die höchsten Gesundheitsrisiken von allen untersuchten Wasserquellen, da es häufig

mit *E. coli* und anderen coliformen Bakterien kontaminiert ist. Oberflächen- und Grundwasser enthalten auch nach der sehr verbreiteten Alaunbehandlung die höchsten Konzentrationen von Metall(oid)en, was erhebliche gesundheitliche Risiken in sich bergen kann. Darüber hinaus führt die Alaun-Behandlung nicht zu einer wirksamen Entfernung von Arsen, so dass kontaminiertes Oberflächen- und/oder Grundwasser auch nach der Behandlung keine sichere Trinkwasserquelle darstellt.

Der Ausbau der Versorgung mit Leitungswasser wird von (inter)nationalen Organisationen und Regierungen als die bevorzugte Lösung angesehen, um den Zugang zu sicherem und sauberem Wasser zu gewährleisten. Allerdings hat die ländliche Mehrheit der Bevölkerung des Mekong-Deltas nur begrenzt Zugang zu Leitungswasser. Im ländlichen Mekong Delta kann während der Regenzeit die Verwendung von Regenwasser und während der Trockenzeit in einigen Fällen die Nutzung des Grund- und/oder Oberflächenwassers unter bestimmten Voraussetzungen empfohlen werden: Die Nutzer müssen sich der damit verbundenen Gesundheitsrisiken bewusst sein und in geeigneten Maßnahmen zur Wasseraufbereitung geschult werden. Solche Maßnahmen beinhalten z.B. die Desinfektion von Oberflächen- und Regenwasser und die Filtration des Grundwassers durch Sand- und Steinfilter, um die Pathogenbelastung einerseits und Metallkonzentrationen andererseits zu reduzieren.

1. The Mekong Delta and its water sources

This chapter presents a general introduction of water sources used by communities in the Mekong Delta (MD), Vietnam for drinking and domestic purposes and associated health-risks. Secondly, general background information about the MD as well as the materials and methods used in this study are presented.

1.1 General introduction

In this section the main water sources used by communities in the MD and the prevalence of water-related diseases in this region are discussed. Also the demand and pressures on water sources as well as governmental responses with respect to water management in Vietnam are presented followed by the hypotheses and objectives of this study.

1.1.1 Drinking and domestic water sources in the Mekong Delta

In the MD, different water sources are used for drinking and domestic (cleaning, washing, cooking) services. Moreover, there is also a difference in the use of water sources for these services between urban and rural areas. In urban areas of the MD, most people have access to improved water sources like piped-water from controlled supply stations (WSP, 2008). In contrast, rural communities in the MD rely more on less-improved water sources like unprotected dug groundwater wells, surface water and rainwater for their daily purposes although water supply stations are also available at some locations (WSP, 2008). In addition, bottled water is also used as a drinking water source in the MD (Özdemir *et al.*, 2011). This study focused on water sources used by rural communities (for drinking and domestic services) in the MD and include:

Household harvested rainwater

Rural communities in the MD use rainwater for drinking and domestic purposes, especially in regions facing freshwater shortage and saline intrusion (Nguyen, 2008). Rainwater is usually collected via rooftop harvesting techniques (Fig. 1a). Typical collection methods include the collection of rainwater via metallic gutters which transport the collected rainwater to storage basins like jars and/or tanks.

Figure 1a – Rainwater harvesting system at a rural household in the Hau Giang Province. Rainwater is collected from roof-tops by gutters (left picture) and transported to storage basins (right picture). This household indicated to use the collected rainwater for drinking (source: Author, 2011).

Although rainwater is relatively easily accessible via these harvesting techniques, the quantity depends strongly on the storage capacity of households. No studies were found regarding the quality of harvested rainwater in the MD.

Surface water from canals and rivers

The MD is characterized for its large density of rivers and man-made canals. Many households in rural areas of the MD are settled near the banks of these waterways. Thus, surface water is easily accessible for many rural inhabitants. Moreover, access to surface water is free of charge. Therefore, people rely on this water for several services including drinking, cleaning and washing (Fig. 1b).

Figure 1b – Typical use of canal water by rural communities in the MD. This image shows a lady washing vegetables in a small canal in the rural areas of Can Tho Province (source: Author, 2011).

Although surface water is easily accessible and a cheap water source, the quality of this water source is usually poor. Isobe *et al.* (2004) for example found high concentrations of coliforms exceeding drinking water guidelines. Also the presence of agrichemicals and heavy metals could pose risks to human health (Sebesvari *et al.*, 2012; Guong and Hoa, 2012). However, most studies focus on main waterways and not on lower order canals as visible in Fig. 1b. Studying the water quality in lower order canals is important since many people rely on them for various services including drinking. Moreover, surface water quality in lower order canals may be considerably different between locations due to variations in land-use systems and/or hydrology and other factors. The influence of these factors should also be assessed to identify hot-spot areas of surface water pollution.

Groundwater from own dug wells

Due to intensive pollution of surface water in the MD, groundwater has become an increasingly important water source for drinking and domestic services since the 1990s (Wagner *et al.*, 2012). Many rural households have an own dug well in order to have access to this water source. Wells are usually equipped with electrical pumps (Fig. 1c) although some households only have a hand-pump.

Although groundwater resources are relatively easily available via these wells, the water quality could be poor and even pose a severe risk to human health. The presence of arsenic in groundwater for example is notorious in Southeast Asia which affects the health of millions of people (Winkel *et al.*, 2008). However, the quality of groundwater and associated health risks in the lower MD is not assessed in detail yet. Furthermore, spatial maps showing groundwater are not developed for the MD, although such maps could be useful to define optimum locations for groundwater extraction.

Rural piped-water supply stations

In 2010 less than 10% of the rural population in the MD was connected to piped-water (SNV, 2010). Therefore the Vietnamese government has developed several programs, usually sponsored by foreign countries and international organizations, to enlarge the amount of water supply stations in rural areas of the MD. In Can Tho Province for example, the Rural Environmental Sanitation and Clean Water Center

Figure 1c – Characteristically own dug groundwater well equipped with pump. This image was taken at a rural household in Can Tho Province and shows the collection of a groundwater sample as a part of the groundwater sampling campaign conducted for this thesis. The owner of this well indicated to use this water for drinking, washing and cleaning (source: Author, 2012).

announced the development of eight new water supply stations to provide clean water to 5,830 households in rural areas of this province (Dangcongsan, 2014). Also in other provinces such as in Soc Trang, new water supply stations are under construction (Fig. 1d). Thus, the number of piped-water supply stations is expected to increase rapidly within the next years.

Water supply stations extract surface- or groundwater and apply various treatment techniques to improve its quality. Households usually have to pay a tariff for the connection and the water use (SNV, 2010). However, to what extend water supply stations actually provide safe water to communities has not been assessed systematically.

Figure 1d – Development of a water supply station in the rural areas of Soc Trang province. The image shows the construction of a water storage tower and the transportation pipes to connect households to the supply station. Behind the two houses (not visible on picture) the water treatment facility will be developed (source: Author, 2012).

Bottled water

Bottled water is mostly used by urban communities in the MD. However, rural households sometimes also use this source for drinking (Fig. 1e).

In the MD, there are hundreds of bottled water brands although the water quality is not always controlled (Reis, 2012). Bottled water manufacturers use surface- or groundwater sources. However, some bottled water brands made false declarations of treatment measures to make this water potable (Reis, 2012). Bottled water quality and associated health-risks were however not investigated in detail in this study since this would require a separate project given the complexity and large variety of bottled water brands in this region.

Figure 1e – Bottled water supply to rural households in the Hau Giang Province. The picture shows a supplier which delivers bottled water to his customers (source: Author, 2011).

1.1.2 Water related diseases

In the rural areas of the MD, around 5.7 million people lack access to safe water sources for drinking, cooking and cleaning which may cause several water-related diseases such as diarrhea, cholera and dysentery (Herbst *et al.*, 2009; WHO, 2013b). An overview of the occurrence of typical water-related diseases measured in 2010 for Vietnam is presented in Fig.2.

Fig. 2 shows that a large proportion of inhabitants in Vietnam are suffering from water-borne diseases. The degree of risk caused by water-borne diseases (and food) in Vietnam is even characterized as 'very high' according to the Central Intelligence Agency of the United States (CIA, 2013). Moreover, the Vietnamese Ministry of Natural Resources and Environment mentioned that the pollution of water resources is responsible for 80% of all diseases in Vietnam (VUFO-NGO, 2014). From all deaths of children with age <5 in Vietnam in 2010, 10% were caused by diarrhea (WHO, 2013b). For comparison, in 2010, this percentage was 3% for Thailand and China while diarrhea was found not to cause deaths for e.g. Australian children (WHO, 2013a). This confirms that the prevalence of water related diseases is a main issue in Vietnam, especially for rural areas where access to improved water sources is more limited compared to urban areas (WSP, 2008). The high rate of water related diseases in Vietnam is thus partially caused by the consumption of contaminated drinking water. Moreover, misconception of risks associated with contaminated water supplies and/or lack of background knowledge and hygienic perceptions are also a main cause of water related diseases (Herbst *et al.*, 2009). For example, some contaminated water sources may be perceived as clean and safe for drinking and consumed directly without proper treatment causing health-risks. Moreover, lack of hand-washing during water collection (hygienic perceptions) could lead to self-induced contamination of drinking water sources. However, the high rate of these typical water related diseases as observed in Fig. 2 could also be caused by various other factors such as lack of proper sanitation, contaminated food and exposure to agricultural waste water (Herbst *et al.*, 2009; Duc *et al.*, 2012). Nevertheless, the risks associated with water sources used for drinking, washing and cleaning should be assessed in order to develop measures to reduce incidents of water related diseases. The high rate of people affected by these diseases show that many families are under significant health stress which significantly affect their quality of life. Moreover, the rate of water related diseases also affects the economical development of Vietnam. The economic loss due to health impacts of polluted water and poor sanitation was US$262 million per year between 1990 and 2004 (including health care, productivity costs and premature death). In addition, the economical loss for domestic water use, fishing and drinking water due to water pollution is US$287 million annually (WSP, 2008). Thus, a set of measurements and programs with the purpose to reduce risks associated with water sources used for drinking and domestic services should be developed in order to stimulate sustainable development in Vietnam and the MD in particular. This will lead to higher quality of life for its inhabitants and will reduce governmental expenditures.

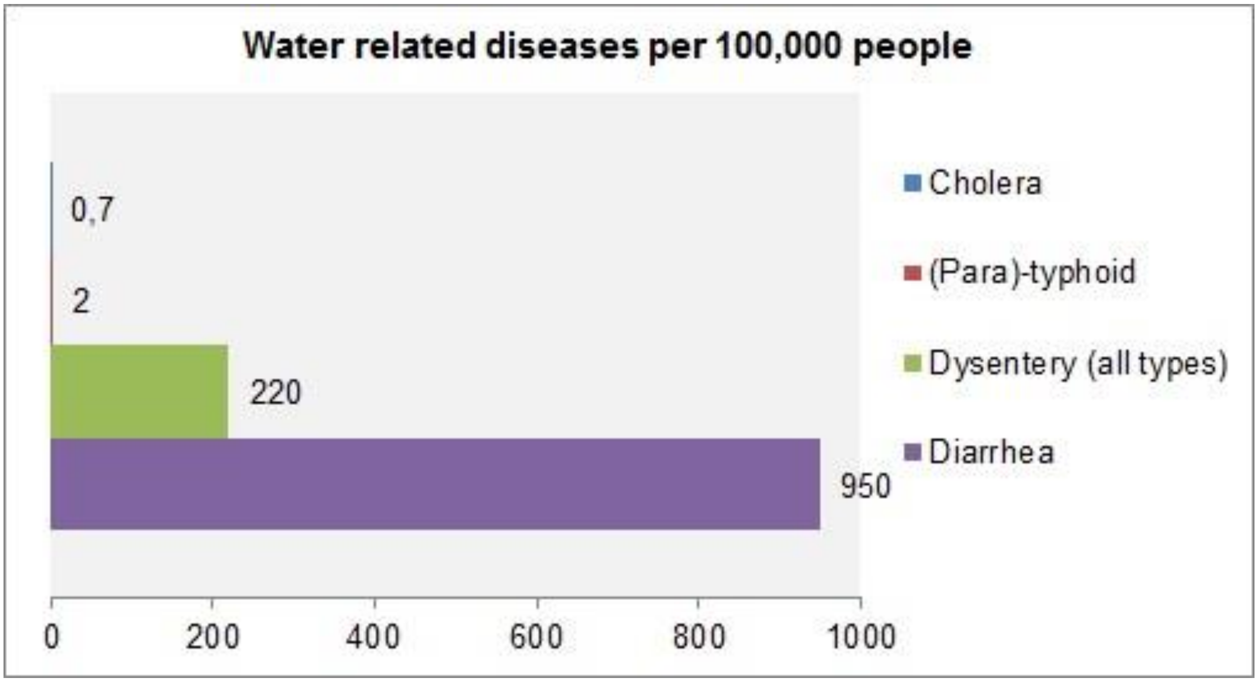


Figure 2 – An overview of the presence of typical water-related diseases in Vietnam for 2010 (graph designed from data of Kotsila, 2012)

1.1.3 Demand and pressures on water sources

In the MD, water sources are intensively used for drinking and other domestic purposes. However, various other services in the MD as well as in other parts of Lower Mekong Basin also demand water which results in quantity as well as quality pressures on water sources. According to the United Nations Water Country Brief of Vietnam for example, main pressures besides drinking water supply on water sources in Vietnam include: i) sanitation; ii) irrigated agriculture; iii) industrial activities and iv) hydropower plants (FAO, 2013). The lack of water and sanitation works, low awareness, inappropriate hygiene behaviors and habits for example are causing negative impact on community's life and the environment in Vietnam (WHO-UNICEF, 2012). More specifically, waste water in the MD from both urban and rural communities are often discharged in rivers and canals without proper treatment causing severe water pollution as well as significant loss of economical value of water sources (WSP, 2008).

The MD is a main agricultural area for Vietnam that is dominated by rice cultivation (GSO, 2012b). Intensive rice cultivation requires large quantities of freshwater which results in salinity intrusion during low flow periods of the Mekong River (Nhan *et al.*, 2010). Intensive agriculture also causes emissions of agrochemicals like nutrients and pesticides to water which could severely pollute aquatic ecosystems (Sebesvari *et al.*, 2012). In addition, pesticides could also be released to the air, potentially contaminating rainwater. Thus agricultural activities in the MD could severely limit the use of water for drinking and domestic purposes. Aquaculture is another important activity in the MD which does not impact water quantity but significantly contributes to water pollution through flushing pond/cage effluents during water exchange (Nhan *et al.*, 2010).

The industrial sector in the MD is mostly dominated by the food-related industry. The industrial activities in Vietnam grow at an average rate of 17% between 2001 and 2006, although this percentage is lower in the MD compared to this national average (ADB, 2010; Garschagen *et al.*, 2012). Nevertheless, industry has major impacts on water quality since only 45% of industrial zones have some form of centralized treatment (ADB, 2010). In addition, air-borne emissions could contaminate rainwater. Industrial activities also affect water quantity since several industrial processes use water for cooling purposes (i.e. electricity producing companies) or need production water which they extract from either surface and/or groundwater (e.g. breweries). Thus, industrial activities have an impact on both water quality and quantity issues.

Hydropower development in the Mekong Basin is proceeding at an increasingly rapid pace (Friend *et al.*, 2009). In the Lower Mekong Basin only, at least 12 potential mainstream hydroplant developments are currently considered which will have significant impacts on the agri- and aquacultural sectors (Pearse-Smith, 2012). Also surface water quality may degrade as a result of these plans similar to the Se San River in Cambodia where elevated turbidity levels were observed after construction of a hydropower dam due to increased river bank erosion (Pearse-Smith, 2012). Moreover, Lee and Scurrah (2011) mention that hydropower dams in the Mekong Basin affect water flow as well as other factors like water quality and the supply of sediments and nutrients in downstream regions. In general, a large and complex variety of activities and processes pressurize the quality and quantity of water sources used for drinking and domestic purposes by rural communities in the MD.

1.1.4 Water management in Vietnam

The government of Vietnam is aware of health risks associated with drinking/domestic water sources and pressures on its water sources. This has lead to a variety of programs and policies on water management and some of these are discussed here.

Water management in the MD started in the early 18th century. However, in those days water management was mainly focused on the widening and digging of canals (Biggs, 2004). The supply and quality of water was still the responsibility of many different ministries and a high levels of fragmentation existed with regard to policy implementation (Waibel, 2010). However in 1996, a water resources sector review concluded the need for a water resources framework plan that had to include various water-related topics including a main focus on domestic water supply (Waibel, 2010). In this context, various policies and guidelines have been developed for the water supply sector in order to secure safe water supplies for its inhabitants. The National Orientation Plan for Water Supply to 2020 for example mentions a goal of 80% urban network coverage and 80 – 100 liters of water supply per capita per day by the end of 2020 (ADB, 2009). The plan's focus is to reach its target mainly via independent public piped-water supply companies in main urbanized agglomerations in Vietnam (ADB, 2009). To date, 73% of inhabitants in the 108 largest cities and towns of Vietnam are connected to piped-water (Jenny, 2013). For rural areas, such as in the MD, different goals have been defined with respect to water supply and quality. In March 2012, the National Target Program for Rural Water Supply and Sanitation 2012 – 2015 was released which has set a goal that 85% of the rural population should have access to hygienic water of which 45% meets water quality criteria set by the national regulation on the domestic water quality (MARD, 2012). This guideline includes eleven water quality parameters including total arsenic and coliforms and defined threshold levels based on the domestic use of water (Ministry of Health, 2009). Except for the development of piped-water supply companies in rural areas, this guideline also includes other improved water sources such as drilled wells, dug well and rain-tanks to reach its target by 2015 (Ministry of Health, 2009). Various foreign countries including Australia, Denmark and the United Kingdom are supporting Vietnam in order to reach its targets for rural water supply by 2015 (AusAID, 2012). Nevertheless to date, many poor people still rely on polluted ponds, open wells and river water for daily purposes (Education Services Australia, 2012). Thus, further developments to provide safe, clean and sufficient water to rural communities is still required to date.

1.1.5 Hypotheses and objectives

Many inhabitants of the MD suffer from water related diseases which are (at least partially) caused by contaminated water sources used for drinking and/or domestic purposes. However, health-related risks associated with these water sources does not only depend on the water quality, but also on the availability of water sources to communities and people's perception towards these sources.

It is assumed that health-related risks associated with drinking/domestic water sources in the MD are mainly explained by the usage of surface- and groundwater because: i) surface water is most likely severely contaminated with organic pollutants and pathogens while groundwater may be contaminated with metals like arsenic as is the case in many regions in Southeast Asia; ii) these sources are most probably easily available in sufficient quantities all year round, are relatively cheap to collect which could make them favorite water sources to use for daily purposes for poor rural communities. It is however also expected that people who use surface- or groundwater do apply some kind of treatment prior to use which could reduce the risk. In contrast, lower health related risks associated with drinking/domestic water sources are expected for people that have access to sufficient rainwater, water from controlled supply stations and/or bottled water since these water sources are probably of a better quality compared to surface- and groundwater. On the other hand, the availability to these sources could be problematic. Rainwater may not be available during the dry season while the development of piped-water supply stations is still limited in rural areas of the MD. Bottled water may be too expensive for rural communities. Rainwater, piped-water and bottled water are most probably perceived as good and safe water sources by rural communities in the MD. In order to test these hypotheses, the following objectives were formulated:

1. identify the usage rate, perceptions and applied treatments for surface-, ground-, rain-, piped- and bottled water sources that are used for drinking and domestic purposes by rural communities in the MD;
2. investigate the quality of household harvested rainwater and assess sources of pollution;
3. investigate, assess and spatially visualize the quality of surface water in lower order canals which are intensively used for daily purposed by rural communities;
4. investigate, assess and spatially visualize the quality of groundwater that rural communities use for daily purposes;
5. investigate the quality of treated piped-water from rural supply stations and assess the perceptions of rural communities towards piped-water;
6. carry out a comparative risk assessment for water sources used for drinking/domestic purposes based on water quality and water quality perceptions to identify the sources with the highest and lowest health-related risks;
7. provide policy-related advices with a main purpose to reduce health-related risks associated with the use/consumption of water sources in the Mekong Delta.

1.2 General Materials and Methods

This section describes the processes with respect to the selection of study areas in the MD. Moreover, this section presents general data regarding topographical, agricultural, soil, water-related, demographic and economic information of the MD. The purpose is to provide insights into the choices that were made in the selection of study sites and to provide important background information about the MD which is relevant for the interpretation of results from the other chapters. The structure of conducted household interviews to assess use and perceptions of inhabitants with respect to drinking/domestic water sources and the selected drinking water quality parameters are also mentioned. Some of the presented data in this section may however be further explained in the following chapters when this was required for submission in peer-reviewed journals. Lastly, an overview of chapters, peer-reviewed articles and attended conferences is listed.

1.2.1 Selection of study areas

This study was conducted in the MD, which is located in the south of Vietnam. However, data collection (household interviews and water samples) throughout the entire MD was difficult since the surface area of the MD is too large to reach every location during one year of field work. Thus, representative areas of the MD were selected and included the Can Tho, Hau Giang and Soc Trang Provinces (Fig. 3).

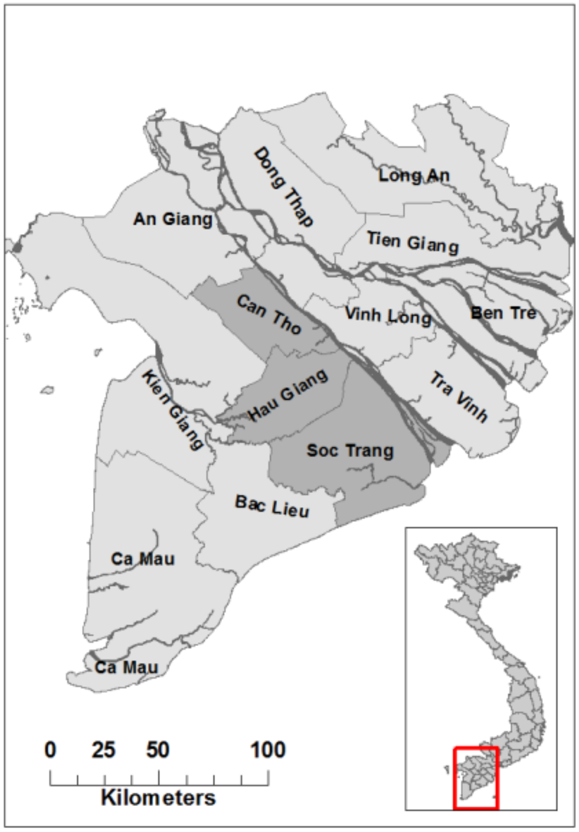


Figure 3 – Overview of the selected study sites (Can Tho, Hau Giang and Soc Trang provinces) in the MD indicated by dark grey color

Representativeness of the study sites was based on land-use characteristics and soil types which are two typical parameters that can be used to distinguish different areas in the MD.

Representative land-use systems include rice fields, fruit orchards, fresh water aquaculture, industrial/urbanized agglomerations and shrimp farming which are all present in the selected provinces. Representative soil types include acid sulphate-, alluvial-, saline- and degraded soils which are also all present in these three provinces. The identification of representative land-use and soil type systems were identified by i) digital maps like a land-cover classification map of 2012 for the MD (Huth *et al.*, 2012) and ii) interviews with local and provincial governmental institutions. An additional reason for the selection of these provinces was their relatively close distance to laboratories to analyze collected water samples.

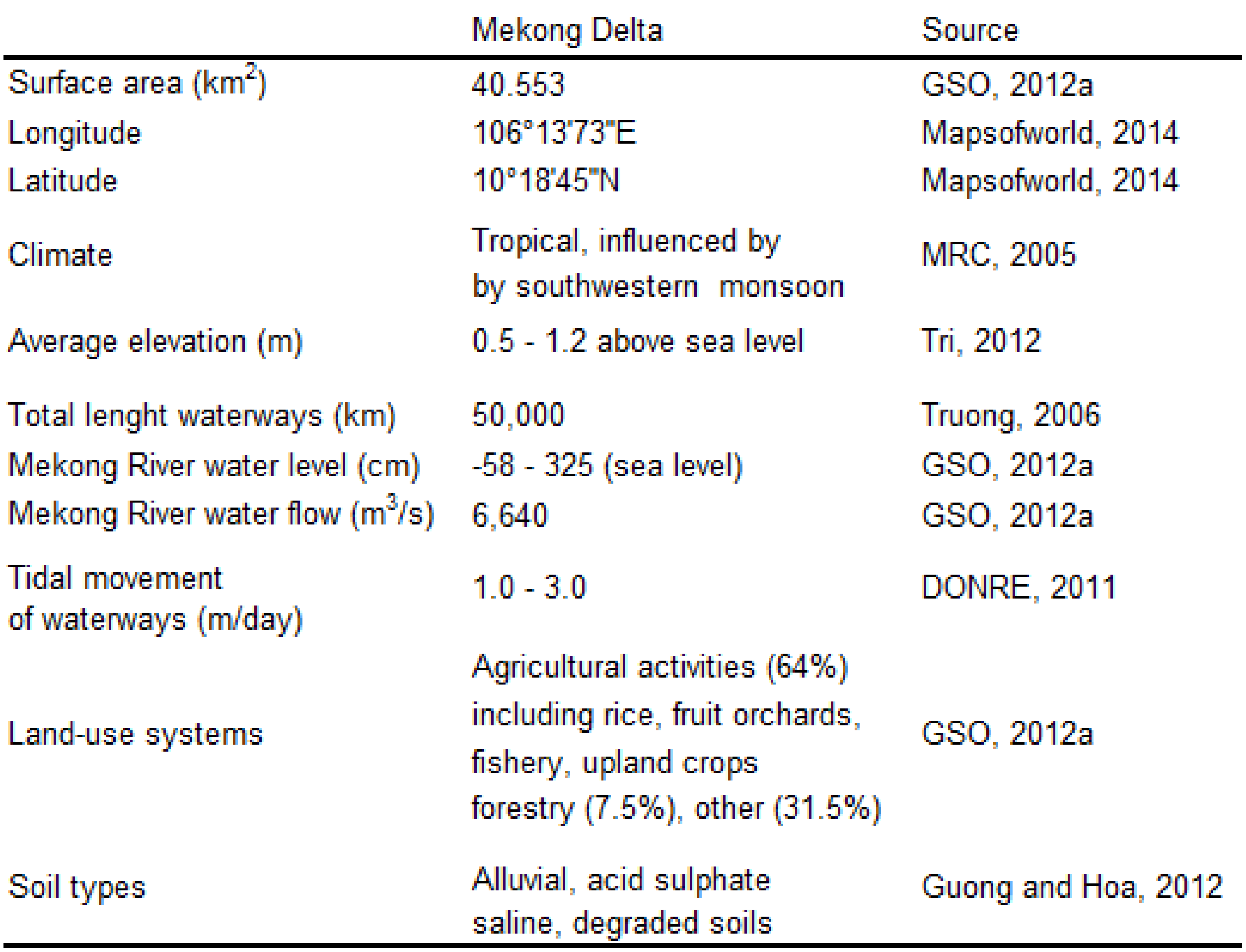
The selection of water sampling locations in the study sites were performed in close collaboration with governmental institutes like the Centre for Natural Resources and Environment (DONRE) and district/commune governmental organizations. These organizations showed potentially interesting water sampling locations and provided additional information regarding water quality, tide tables, agricultural activities and demographic data of the region. Furthermore, the DONRE's of the three selected provinces successfully arranged the required research permissions in order to carry out the field work in the study sites (water sampling and household interviews).

1.2.2 General and study related characteristics of the Mekong Delta

Basic topographical, geographical, climate, soil, land-use and water-related data are presented in table 1.

Table 1

Topographical, agricultural, soil and water-related characteristics of the Mekong Delta



	Mekong Delta	Source
Surface area (km^2)	40.553	GSO, 2012a
Longitude	106°13'73"E	Mapsofworld, 2014
Latitude	10°18'45"N	Mapsofworld, 2014
Climate	Tropical, influenced by by southwestern monsoon	MRC, 2005
Average elevation (m)	0.5 - 1.2 above sea level	Tri, 2012
Total lenght waterways (km)	50,000	Truong, 2006
Mekong River water level (cm)	-58 - 325 (sea level)	GSO, 2012a
Mekong River water flow (m^3/s)	6,640	GSO, 2012a
Tidal movement of waterways (m/day)	1.0 - 3.0	DONRE, 2011
Land-use systems	Agricultural activities (64%) including rice, fruit orchards, fishery, upland crops forestry (7.5%), other (31.5%)	GSO, 2012a
Soil types	Alluvial, acid sulphate saline, degraded soils	Guong and Hoa, 2012

Topographic and geographic data

The Mekong Delta latitude and longitude is 10°18'45''N and 106°13'73''E respectively and is located in the tropical zone. Main cities include My Tho in the east, Chau Doc in the northwest and Ca Mau in the south while Can Tho City is located in the centre of the MD. The land was formed relatively recently from alluvial deposits within the past 10,000 years from the Himalaya Mountains (Guong and Hoa, 2012). The elevation is, except near the border of Cambodia, close to sea level (Table 1).

Climate

The tropical climate of the MD results in relatively humid conditions of 81% all year round (GSO, 2012a). The southwestern monsoon causes dry and wet seasons (Delta Alliance, 2011). Rainfall events occur mainly in the wet season between May – October. However, in some years rainfall events do also occur in the dry season (Fig. 4). Peak rainfall is generally in the months July – September. The yearly average amount of rainfall is between 1,600 – 2,600 mm, varying per location and between years (Delta Alliance, 2011; GSO, 2012a). The average monthly air temperatures are above 25°C during the entire year with the highest air temperatures measured in March and April (Fig. 4).

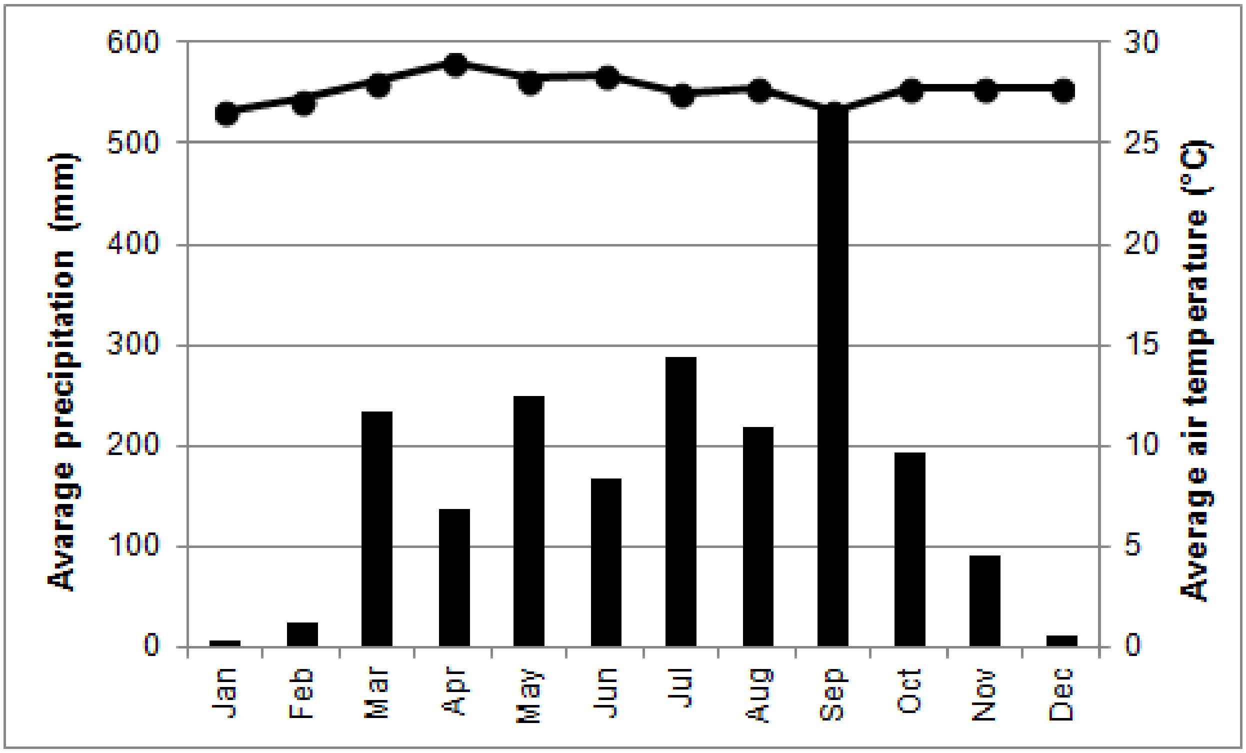


Figure 4 – Average monthly rainfall (mm) presented in bars and air temperatures (°C) presented as black line with dots in Ca Mau Province in 2012 (source: GSO, 2012a).

Waterways

The MD knows a large variety of natural and artificial waterways. The Mekong River is the largest waterway of the MD and it origin is located in the Tibetian Plateau in China and flows through Lao PDR, Thailand, Cambodia and Vietnam. The total length of the Mekong River from origin in China to the mouth in Vietnam is around 4,800 km and is ranked as the 10th largest river of the world based on mean annual flow at the mouth (MRC, 2005).

Near Phnom Penh in Cambodia, the Mekong River splits into nine branches through the Mekong Delta, Vietnam before its discharges to the South China Sea (referred to as the East Sea in Vietnam). Besides these main branches, a dense network of artificial canals is present in the Mekong Delta, with a total length of nearly 50,000 km (Truong, 2006). In general, the waterways in the Mekong Delta can be characterized in three different orders and include i) primary canals that directly discharge water from (agricultural) fields; ii) secondary canals include larger waterways that collect water from primary canals; iii) main canals and rivers are the largest waterways that collect water from secondary canals and water from upstream regions. Besides seasonality, the water flow of waterways in the Mekong Delta is also strongly influenced by a diurnal tidal regime. These tidal movements cause daily water level fluctuations up to 3 meters depending on the distance to sea, density of canals, seasonality and artificial water works like dykes and sluices (DONRE, 2011).

Land-use

A majority of the surface area of the MD is used for agricultural production with nearly 50% covering rice (GSO, 2012a). Therefore, the MD is also known as the 'rice granary' of Vietnam. Also fruits are intensively cultivated such as mango, banana, pomelo and many others. Upland crops such as lettuce, sugar cane, maize, sweet potatoes are also present although cultivated in lower quantities compared to rice and fruits. Pig farming is dominating the livestock sector in the MD and accounts for more than 70% of total meat production in Vietnam (Fisher and Gordon, 2008). Other relevant livestock production includes poultry and cows. Ducks farms are also widely present in and around canals, partially to control snail plagues but also for its meat and eggs. The fresh water aquaculture sector has significantly increased in the last years due to raised export and is present in almost all inland provinces of the Mekong Delta. In fresh water ecosystems, catfish production is most popular (Sebesvari *et al.*, 2012). In coastal regions, shrimp cultivation is the most dominant form of land-use although other crops like rice and upland crops are also cultivated in the wet season.

Besides agricultural activities, the MD also has main industrial zones and urbanized agglomerations. Industries in the Mekong Delta mostly focus on food-related processes, the production of agricultural and aquaculture inputs and related industries in equipment and machinery. Also textile and building material production is present (Garschagen *et al.*, 2012). The largest industrial/urbanized agglomeration of the MD is located in Can Tho City.

Soil types

The MD can be classified based on soil types in five main categories according to Minh (2006): i) alluvial soils are mostly present along main rivers, like the Mekong River, and are the most productive soils for rice, fruit orchards and upland crops; ii) acid sulphate soils are one of the most dominant soil types, occupying about 40% of the total agricultural area in the MD (Guong and Hoa, 2012). The acid conditions of these soils results in the leaching of toxic metals to water which negatively affect agricultural production, fish farming and the use of surface water for drinking; iii) saline soils are present in coastal regions and although nutrient levels are high, the salinity levels limit plant growth; iv) degraded soils are mostly present in coastal regions in the form of sandy ridges and sand bars. Nutrient concentrations and microbial activities in these soils are generally low although rice and upland crops are cultivated on these soils.

Demographics and socio-economic attributes

The MD has a total population 17.4 million in 2012 (Table 2). The three main ethnic groups include: i) Viet or Kinh that account for 80% of the total population of the MD; ii) the Khmer people who live mainly in coastal provinces and in An Giang province and iii) Chinese people who live scattered in smaller communities over the entire MD (Nam *et al.*, 2000). The MD is the most densely populated region in Vietnam. However, the the population growth is below 1% since the year 2000 (Garschagen *et al.*, 2012). Nevertheless, the high population density may be a main pressure on the quality of life for its inhabitants when agricultural services, economical growth, educational facilities, health care and sufficient drinking water supplies do not evolve in line with the population density. Garschagen *et al.* (2012) found that under stress from multiple economic and environmental pressures and risks, small-scale farmers in the MD have difficulties securing a minimum level of profitability and a stable livelihood base. The urban/rural ratio of 15.6% (Table 2) shows that a majority of people (around 85%) live in the rural areas. The ratio in the MD is lower than the average of Vietnam and confirms the rural nature of this region (Nam *et al.*, 2000).

Reported economical growth between 1991 – 2012 is almost constantly above 5% (Nam *et al.*, 2000; GSO, 2012a). A main reason for this economical growth is the improved de-collectivization, expansion, intensification and diversification of the agricultural sector, which is the largest economical driver of the region (Garschagen *et al.*, 2012). As a result, poverty rates in the MD reduced from 23% in 2002 to 10.6% in 2012 (Garschagen *et al.*, 2012; GSO, 2012a). Nevertheless, the economic development in the MD is lower compared to the average economical growth of Vietnam (Nam *et al.*, 2000) and many developments in the socio-economic sphere like education and housing conditions are behind the national average (Garschagen *et al.*, 2012).

A main reason for the lower economical development of the MD compared to other regions in Vietnam could be caused by low industrial development (Garschagen *et al.*, 2012). The unemployment rate in the MD of roughly 2.2% in 2012 (Table 2) was relatively low when compared to the unemployment rate of higher than 10% in 1998 (Nam *et al.*, 2000). This confirms the main economical improvement over the last years. On the other hand, many people are still under-employed (Nam *et al.*, 2000) and do not earn enough income to supply their daily needs. In the rural areas, income levels are generally low and the work load and income fluctuates severely between seasons due to the harvesting and selling of agricultural products. This could explain the relatively high poverty rate compared to the unemployment rate as reported for 2012 (Table 2). In general, the MD's economy has significantly increased in the last years which resulted in a decrease in poverty rates. Nevertheless, many people (especially in rural areas) are still living under poor conditions with minimum living standards. Therefore, many people do not have access to safe drinking water supplies and do not have sanitized toilet facilities.

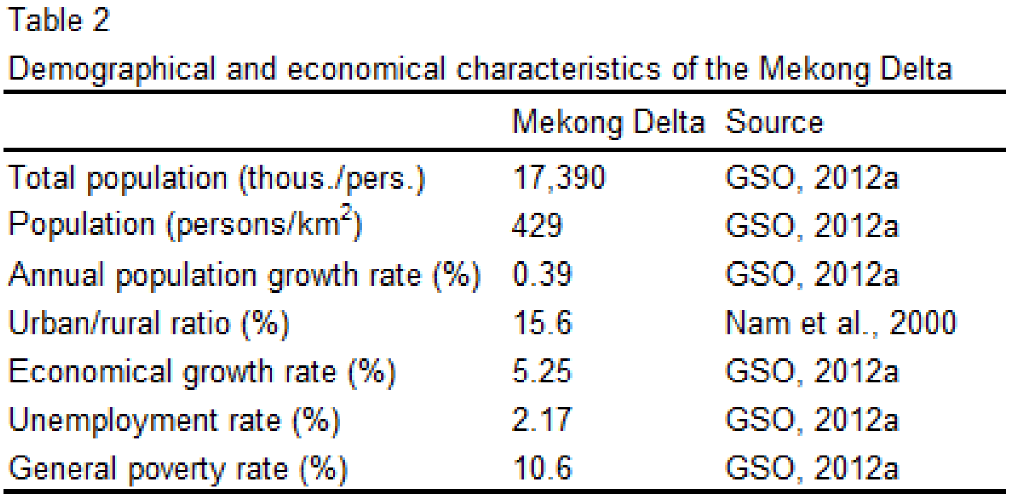


Table 2

Demographical and economical characteristics of the Mekong Delta

	Mekong Delta	Source
Total population (thous./pers.)	17,390	GSO, 2012a
Population (persons/km^2)	429	GSO, 2012a
Annual population growth rate (%)	0.39	GSO, 2012a
Urban/rural ratio (%)	15.6	Nam et al., 2000
Economical growth rate (%)	5.25	GSO, 2012a
Unemployment rate (%)	2.17	GSO, 2012a
General poverty rate (%)	10.6	GSO, 2012a

1.2.3 Household interviews

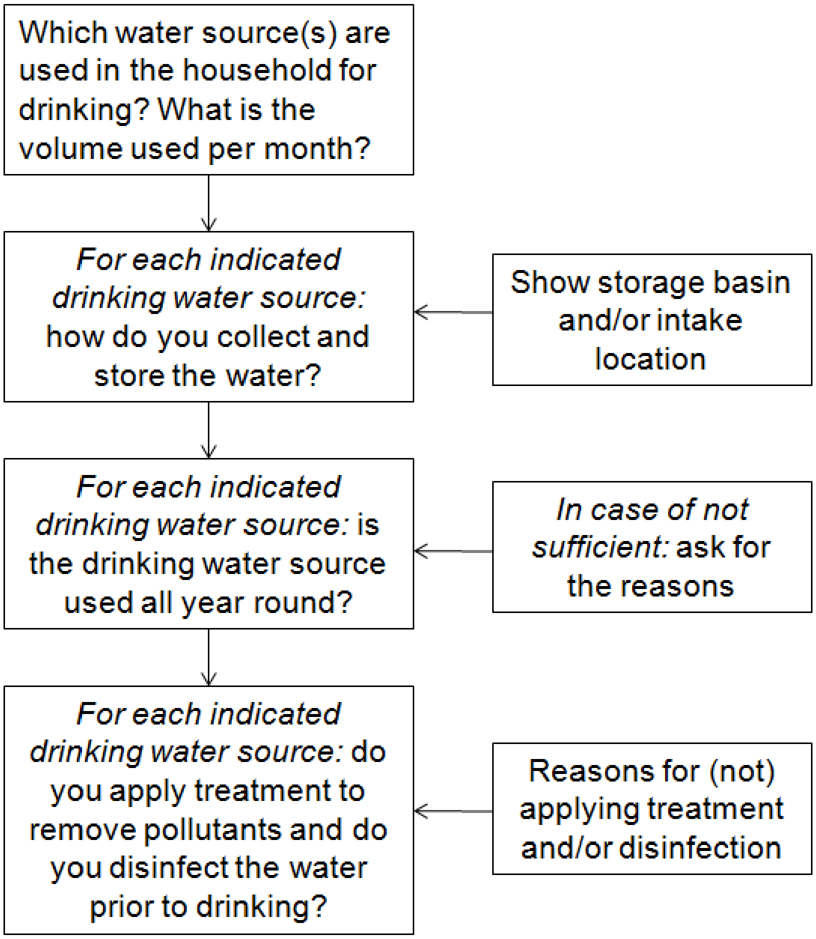
One part of the risk assessment associated with water sources was to investigate the actual use and perceptions of rural communities with respect to available water sources. Therefore, a total of 542 household interviews were conducted at the study sites with a predefined questionnaire, which mainly focused on drinking water (Table 3).

The aim of the questionnaire was: i) to assess the sources of water used for drinking and to define whether the mentioned sources function as main or additional drinking water supply for the household; ii) to investigate the storage and handling practices with respect to different drinking water sources; iii) to assess potential differences in the use of drinking water sources between seasons and iv) to assess the type and rate of water treatments applied to drinking water sources prior to consumption. These aspects are all relevant for the risks associated with drinking water sources since they influence the exposure to contaminated drinking water. Questions regarding storage mechanisms, handling practices and applied household water treatments were asked since this indicates the perceptions of households with respect to their drinking water sources. The responses of people with respect to used drinking water sources were checked on location by visualizing the extraction and/or intake locations of the drinking water sources. The climate in the MD is characterized by wet and dry seasons which could also impact the availability of certain drinking water sources and has therefore been assessed by asking questions whether the storage capacity of drinking water sources was sufficient to supply a household for an entire year. In addition, the number of family members of interviewed households was determined to further assess whether the indicated drinking water volumes and storage capacity were sufficient for the entire household.

Households were selected randomly in the study sites but were geographically spread in order to cover the three provinces. All household interviews were conducted in rural areas and in small villages only since about two third of the population in those areas are not connected to any form of piped-water supply systems (ADB, 2009). Instead, cities were not considered in this study since 60% - 90% of the population has access to piped-water (ADB, 2009).

Besides the above mentioned questionnaire, household were also asked to identify the water sources used for domestic services (washing, cleaning, cooking), since this could be another pathway of exposure to contaminated water which may cause health concerns.

Table 3 – Structure of the questionnaire conducted at rural households in Can Tho, Hau Giang and Soc Trang Provinces of the MD to assess the water sources used for drinking and perceptions towards the water sources (n=542)



1.2.4 Selected water quality parameters

Another dimension of the research was to assess the water quality of sources used for drinking/domestic purposes. The quality of water sources was defined for salinity, nutrients, heavy metal(loid)s and microbial indicator bacteria (Table 4).

Salinity is represented by the concentrations of Na and Cl in water. Saline water does not directly lead to health-related risk when consumed by humans. However, saline water is not suitable for drinking due to unfavorable taste as well as for other functions like irrigation of crops. From the selected nutrients, NO_2 and NO_3 were chosen due to defined health-related drinking water guidelines set by the WHO (2011). The other selected nutrients do not pose direct risks to human health but are included in this study to investigate and assess the presence and sources of nutrient contamination in water sources in the MD.

Except for Mg, all selected metals have defined drinking water quality standards since elevated concentrations in water may cause severe health-related concerns (WHO, 2011). A metal of particular interest is As since this metal may cause severe illnesses including gangrene in legs and cancer (Anawar *et al.*, 2002). The amount of metals selected in this study is however also defined by the available metals in the standard solution that was available to calibrate the ICP analyzer. Water supplies can be contaminated with a large range of pathogens including bacteria, viruses and protozoa. The analysis of all these pathogens in drinking water sources is difficult, time consuming and extremely expensive thus there is a need to define an indicator bacteria that represents microbial pollution of water sources. *E. coli* is widely accepted as an indicator bacteria, is included in many drinking water standards and has therefore been selected in this study as well (Edberg *et al.*, 2000). In addition, other coliforms and total coliforms bacteria were analyzed since these bacteria could also indicate the presence of pathogens and are therefore included in drinking water standards set by WHO (2011).

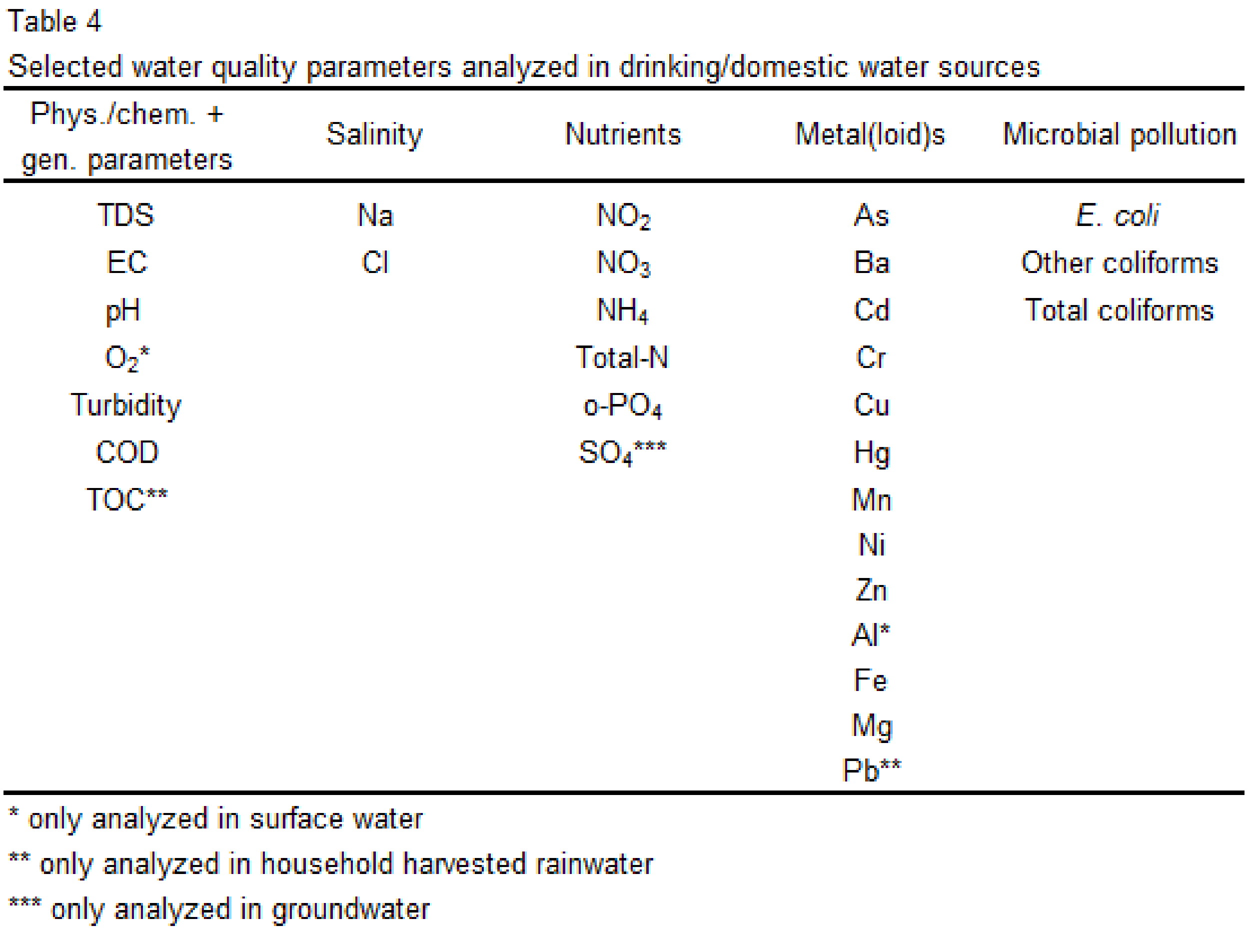


Table 4

Selected water quality parameters analyzed in drinking/domestic water sources

Phys./chem. + gen. parameters	Salinity	Nutrients	Metal(loid)s	Microbial pollution
TDS	Na	NO_2	As	*E. coli*
EC	Cl	NO_3	Ba	Other coliforms
pH		NH_4	Cd	Total coliforms
O_2*		Total-N	Cr	
Turbidity		o-PO_4	Cu	
COD		SO_4***	Hg	
TOC**			Mn	
			Ni	
			Zn	
			Al*	
			Fe	
			Mg	
			Pb**	

* only analyzed in surface water

** only analyzed in household harvested rainwater

*** only analyzed in groundwater

Besides water quality parameters representing salinity, nutrients, metal(loid)s and microbial indicator bacteria, some general parameters were analyzed as well (Table 4). On the one hand, these parameters function as control parameters to assess whether observed nutrient, salt and metal concentrations are reliable (i.e. comparison of TDS and EC values with salt and metal concentrations). On the other hand, general parameters can be used to assess the sources and reasons of pollution (i.e. relationship between pH and turbidity with metal concentrations).

1.3 Outline of the thesis

This section mentions the content of chapters, the published articles in peer-reviewed journals and presented results in international conferences.

1.3.1 Chapters Description

Chapter 1: provides general background information regarding water sources that are used for drinking and domestic purposes by rural inhabitant of the MD. Furthermore, the necessity to investigate the quality and associated health risks related to water sources is presented. This chapter also shows general characteristics of the MD that are useful for the interpretation of results from the other chapters. Also the reasons for selection of the study sites, household interviews and water quality analyses are discussed.

Chapter 2: presents the rate of surface-, ground-, rain-, piped- and bottled water used for drinking and domestic services by rural communities in the MD. Also differences in the use of water sources between seasons are discussed.

Chapter 3: describes the quality of household harvested rainwater. This chapter also assesses the causes of pollution in this water source from spatial (industry, main roads, coastline) and local (roof types, storage system and duration) conditions. Furthermore, possible pollution sources after collection at the point-of-use are discussed.

Chapter 4: presents the surface water quality in lower order canals of the MD which are intensively used by rural communities in the MD for their daily needs. The water quality in lower order canals is also compared with water quality from main waterways like rivers. Moreover, this chapter shows the relationship between soil types, land-use systems, and distance to main waterways with the quality of surface water in the lower order canals via a Principal Component Analysis. In addition, surface water quality is presented via spatial maps developed by regression models. Temporal fluctuations of surface water quality caused by the tidal regime and seasonality are discussed.

Chapter 5: presents the quality of groundwater that was collected from dug wells by rural communities. This chapter also shows and discusses the sources and processes that cause contamination of groundwater bodies in the selected study sites. The influence of well depth on groundwater is shown as well. Groundwater quality is, based on Gaussian Statistical Simulation, spatially visualized for four representative water quality parameters which show the locations of (potential) hot-spot areas of pollution. Lastly, a comparison of groundwater quality observed in this study with groundwater quality in other regions of Southeast Asia is presented.

Chapter 6: examines the quality of supplied piped-water in rural areas of the MD. This chapter also shows some locations of water supply stations were the water quality exceeds international drinking water guidelines and discusses possible causes of pollution. Also the perception of rural communities towards piped-water is presented.

Chapter 7: presents a comparative risk assessment for water sources (raw and under household stored conditions) used by rural communities in the MD for microbial pollution, metals, nutrients and salinity. The risk assessment is based on water quality and people perceptions towards water sources and is ranked via a calculated ‘risk index’.

Chapter 8: provides the general conclusions of this study based on the results presented in the former chapters. Moreover, policy-related recommendations are provided which focus on how to secure safe drinking and domestic water supplies for rural communities for present and future generations.

1.3.2 Peer-reviewed articles

This is a cumulative thesis and results of this study are published in peer-reviewed journals:

Wilbers, G., Sebesvari, Z., Rechenburg, A., Renaud, F.G., 2013. Effects of local and spatial conditions on the quality of harvested rainwater in the Mekong Delta, Vietnam. Environ. Pollut. 182, 225-232.
This article contains the results from chapter 3.

Wilbers, G., Becker, M., Sebesvari, Z., Renaud, F.G., 2014. Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. Sci. Total Environ. 485-486, 653-665.
This article contains the results from chapter 4.

Wilbers, G., Sebesvari, Z., Renaud, F.G., Spatial visualization of groundwater quality contamination in the lower Mekong Delta, Vietnam: pressure of salinity intrusion and identification of health-related risks (submitted). This article contains the results from chapter 5.

Wilbers, G., Sebesvari, Z., Renaud, F.G. Piped-water supplies in rural areas of the Mekong Delta, Vietnam: water quality and household perceptions (submitted).
This article contains the results from chapter 6.

Wilbers, G., Sebesvari, Z., Lap, N.V., Rechenburg, A., Renaud, F.G. A comparative risk assessment associated with the microbial quality of drinking water sources in the Mekong Delta, Vietnam (in preparation).
This article contains results from parts of chapter 1, 2 and 7.

1.3.3 Attended conferences

The results of this study were presented in two international conferences:

Wilbers, G., Sebesvari, Z., Renaud, F.G., Becker, M., 2013. The relationship between land-use and tidal regime with surface water quality in the Mekong Delta, Vietnam. Poster Presentation. Land-use and Water Quality conference, The Hague, The Netherlands, 10 – 13 June, 2013.
(results from chapter 3)

Wilbers, G., Sebesvari, Z., Renaud, F.G., Rechenburg, A., Kistemann, T., 2013. Microbial health risks associated with drinking water sources in the Mekong Delta, Vietnam. Oral Presentation. Environmental Health Conference, Boston, Massachusetts, United States of America, 3 – 6 March, 2013.
(results from chapters 1, 2 and 7)

2. Usage of water sources

Various water sources are used by rural communities in the MD for drinking and domestic purposes. This chapter presents an overview of the rate of water sources used for different services and between seasons.

2.1 Drinking water services

The usage of water sources for drinking services by rural communities in the MD fluctuates during the wet and dry season (Fig. 5).

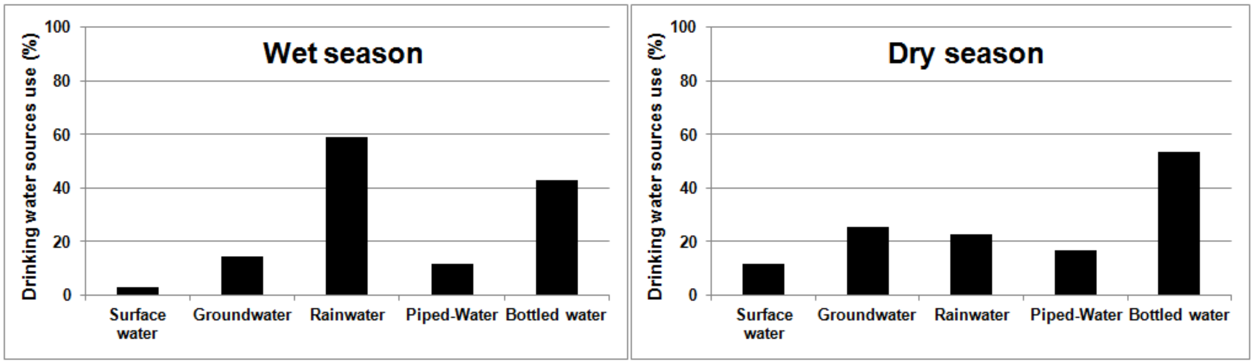


Figure 5 – Water sources used for drinking by rural households in the wet and dry season respectively based on the interviews in the Can Tho, Hau Giang and Soc Trang provinces (n=542)

In general, most people use two or more drinking water sources depending on location, financial situation of the household and (seasonal) availability of a drinking water source. Rainwater is the most frequently mentioned drinking water source in the wet season since it is ranked high for physical conditions like color, taste and smell. Moreover, it is a cheap source and relatively easy to access via roof harvesting. Households using rainwater for drinking mentioned this as the main drinking water source. Nevertheless, only 41% of the households using rainwater indicated to have sufficient storage capacity to cover for the needed water volume during the dry season (November - April). Thus, 59% of the households using rainwater typically rely on other drinking water sources during the dry season. The absence of rainwater in the dry season leads to an increase in the use of bottled- and groundwater sources mostly. However, also surface water and piped-water are more frequently mentioned as a drinking water source in the dry season compared to the wet season. Bottled water is the other most popular drinking water source although it is generally not mentioned as a main water source used for drinking. A majority of the respondents indicated to use bottled water as an additional source, i.e during the dry season when rainwater is not available or only provide bottled water to the most vulnerable family members like children and elderly people. Some households only use bottled water in cases they have enough financial resources to afford it. The use of groundwater for drinking varies considerably between the investigated study sites. Especially in regions were groundwater is affected by saline intrusion (e.g. Hau Giang and Soc Trang provinces), its use for drinking is strongly reduced (Wilbers *et al.*, submitted b). Most interviewees also referred to the bad smell of groundwater which is most probably caused by high iron and manganese concentrations (Buschmann *et al.*, 2008). Nevertheless, groundwater is considered as a valuable and major drinking water source, especially in the dry season, for 26% of the interviewed households. Piped-water supplies and surface water are less frequently mentioned as a source for drinking water. Piped-water supplies are not widely available in the rural areas of the MD which explains the relatively low percentage of people that indicated to use piped-water. In addition, many households have little interest in piped-water supplies even if a connection is available due to high connection fees and the preference for other water sources (Reis and Mollinga, 2009). Although surface water is commonly available all year round from rivers and canals, this water source is the least preferred drinking water source. Most people indicated to perceive this water source as heavily polluted. Surface water is however sometimes used as an additional source during the dry season when rainwater is scarce. Also households who lack financial resources for a groundwater well, piped-water supply or bottled water use this freely accessible source.

Other studies related to drinking water sources use in the MD also show that rainwater is the most popular drinking water source (Özdemir *et al.*, 2011; Herbst *et al.*, 2009), but significant differences between studies were also found. Herbst *et al.* (2009) reported that water supply stations are most popular after rainwater and bottled water in An Binh district near Can Tho City which was not surveyed in our study. This finding suggests that the share of different drinking water sources in use can fluctuate drastically between locations. Also in our study, differences in the use of drinking water sources were observed between regions. In Soc Trang province for example, none of the households indicated to use surface water in either the dry and wet season at all due to strong saline intrusion. In some districts of Hau Giang province, none of the households indicated to use groundwater for drinking due to strong saline taste. Thus, the indicated water use as shown in Fig. 5 does not necessarily represent the actual use for every village/district in those provinces but provides a general overview for the entire study region.

2.2 Domestic water services

The rate of water sources used for domestic services is completely different compared to water sources used for drinking (Fig. 6).

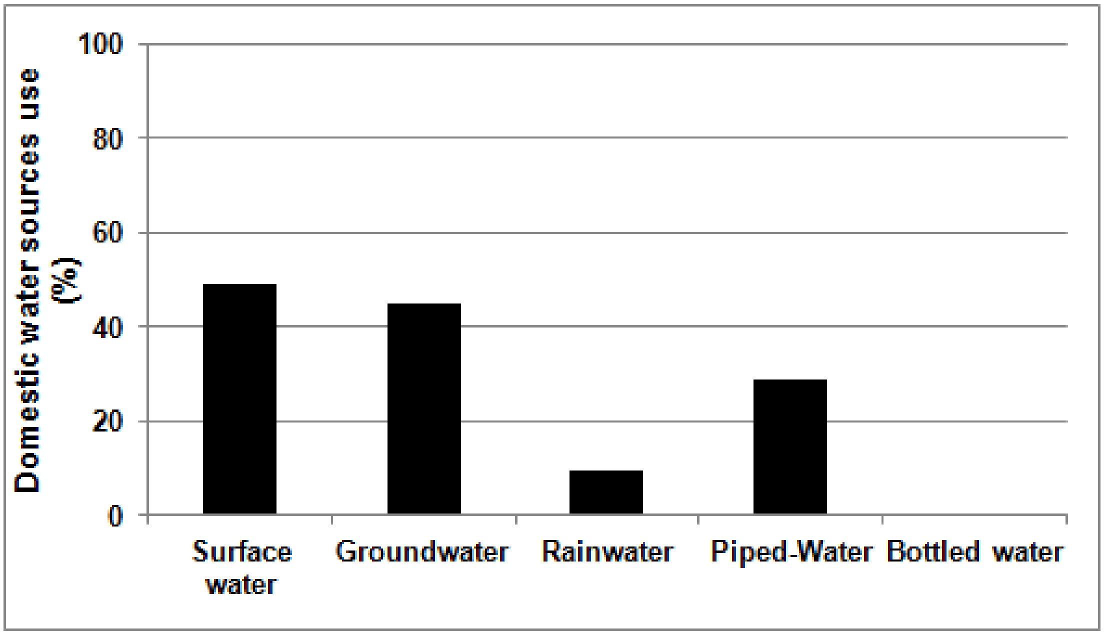


Figure 6 – Water sources used for domestic services by rural households based on the interviews in the Can Tho, Hau Giang and Soc Trang provinces (n=542)

No relationship between water sources used for domestic services and seasonality was observed since people rely on water sources for these services that are easily accessible, cheap and available all year round. One of the most popular water sources indicated was surface water due to its presence at almost all locations in the MD. Surface water used for domestic purposes (cooking, washing, cleaning) is sometimes stored and pre-treated with alum prior to use to remove visible pollutants and suspended solids. However, visual observations during field visits also revealed that raw surface water is intensively used for several domestic functions including: i) washing in canals; ii) brushing teeth and rinsing with raw surface water directly in the canal and iii) cleaning of cutlery in canals including the rinsing of bottles that are used for drinking. Thus, many people are exposed to this water source. Another major domestic water source is groundwater. In general, people that have (or have access to) a groundwater wells use this water source for various domestic services. People prefer groundwater above surface water for domestic services due to lower observed pollutants. Even when groundwater has a saline taste or a bad smell, people still prefer this source above surface water. However, not all people can financially afford to construct a groundwater well and therefore have to rely on other water sources for daily use such as surface water. Although rainwater is a scarce water source in the dry season for many inhabitants of the MD, 9.8% of interviewed households indicated to use this water source for both drinking and domestic purposes. This can be explained by the fact that some households made major investments to collect and store rainwater in large quantities. For example, some households constructed large concrete basins that contain several cubic meters of rainwater while others invested in large quantities of jars (20 – 30) to enlarge storage capacity. The amount of people who indicated to use piped-water for domestic services (28.8%) is higher compared to its usage for drinking (11.6 – 16.6% in the wet and dry season respectively). This means that a large proportion of people only use piped-water for domestic services although its intention is to provide safe water supplies above the generally polluted natural water sources. Bottled water is not used for domestic services and only applied as a drinking water source.

Some households also reported to use several water sources for domestic purposes like the use of surface water for washing and cleaning and piped-water for cooking. Therefore, the total percentage of water sources used for domestic purposes is higher than 100%. Similar to the use of drinking water sources, differences in the use of domestic water sources can be observed between villages/districts. In Soc Trang province for example, none of the household mentioned to use surface water even for domestic services due to high salinity. Therefore, Fig. 6 only represents an average for the entire study region.

3. Effects of local and spatial conditions on the quality of harvested rainwater in the Mekong Delta, Vietnam

Abstract

The objective of this study was to assess the quality of harvested rainwater in the Mekong Delta (MD), Vietnam for local (roof types, storage system and duration) and spatial (proximity of industry, main roads, coastline) conditions. 78 harvested rainwater samples were collected in the MD and analyzed for pH, turbidity, TDS, COD, nutrients (NH_4, NO_3, NO_2, o-PO_4), trace metals and coliforms. The results show that thatch roofs lead to an increase of pollutants like COD (max. 23.2 mgl^{-1}) and turbidity (max 10.1 mgl^{-1}) whereas galvanized roofs lead to an increase of Zn (max. 2.2 mgl^{-1}). The other local and spatial parameters had no or only minor influence on the quality of household harvested rainwater. However, lead (Pb) (max. 16.9 μgl^{-1}) and total coliforms (max. 102,500 $CFU100ml^{-1}$) were recorded at high concentrations, probably due to a variety of household-specific conditions such as rainwater storage, collection and handling practices.

3.1 Introduction

There are many types of water sources used for drinking purposes in the rural areas of the Mekong Delta (MD), Vietnam as well as other similar regions in South-East Asia. However, potential sources such as groundwater and surface water are used less extensively due to poor physical conditions of some parameters such as smell, taste and color which lead to a reluctance to consume these water sources for drinking (Herbst *et al.*, 2009). Moreover, piped-water access in rural areas of the MD is still limited to date with only 8-12% coverage (SNV, 2010). Rainwater is advocated as a reliable drinking water source by residents and governmental institutions since it does not have the disadvantages mentioned above for other sources (Özdemir *et al.*, 2011) and is economically feasible. There is, therefore, an opportunity to further encourage the use of rainwater as a drinking water source in the MD. For example, in Soc Trang province a governmental program was developed to enlarge the rainwater storage capacity in water supply stations (Vietbiz24, 2010). Snelgrove and Patrick (2009) suggest measures to increase the volume of harvested rainwater, and to improve the durability and affordability of storage tanks in Vietnam in order to increase the usage of rainwater as a drinking water source. Similar recommendations were made for other countries such as Bangladesh where rainwater is proposed to be a potential alternative source for drinking, cooking and dishwashing purposes in arsenic contaminated areas (Islam *et al.*, 2010). In Australian cities, rainwater is also proposed to be a feasible alternative water source (Zhang *et al.,* 2009). Recent studies, however, show concerns with respect to physico-chemical and especially microbial contamination of household harvested rainwater (HHR). Meera and Mansoor Ahammed (2006) concluded that HHR can be heavily contaminated with pathogenic micro-organisms world-wide. A study in Australia showed the presence of a large variety of pathogens including *E. coli*, enterococci, *C. perfringens*, and *Bacteroides* spp. (Ahmed *et al.*, 2008) while Fewtrell and Kay (2007) indicated the presence of a large variety of pathogenic micro-organisms in HHR in many other countries as well. Heavy metal pollution of HHR is another concern, although reported concentrations are mostly well below international water quality standards (Mendez *et al.*, 2011). However, In New Zealand Pb and Cu concentrations exceeded drinking water guidelines at some locations (Simmons *et al.*, 2001).

Most studies regarding contamination of rainwater focus on the influence of roof types. However, there are significant differences between similar studies in different regions. For example, Mendez *et al.* (2011) concluded that green roofs are responsible for highest concentrations of microbial pollution, DOC and As in HHR. Although Yaziz *et al.* (1989) found similar results, their study also showed that Pb concentrations were consistently high regardless of roof type. Most studies found microbial indicator bacteria in HHR; however, Lee *et al.* (2012) only found low to undetectable concentrations of *E. coli* in rainwater harvested from galvanized steel and clay tiles in South-Korea. Other studies emphasized the effects of spatial specific conditions on the quality of harvested rainwater. A study in the USA concluded that the presence of Zn and Cu were most probably caused by industrial emissions given the high concentrations of these substances in rainwater samples that were collected without roof contact (Chang *et al.*, 2004). Mantovan *et al.* (1995) found variations in rainwater quality caused by population densities and industrial areas while Thomas and Greene (1993) reported Pb concentrations two-folds higher than WHO drinking water guideline values near an industrial zone. Despite the large differences between studies, roof types and spatial conditions such as the presence of agglomerations seem to influence harvested rainwater quality. Aside from these parameters, behavioral factors such as handling and hygienic perceptions are expected to influence the quality of HHR through the lack of hand-washing after, for example, using sanitation facilities (Herbst *et al.*, 2009).

To date, there are only a few investigations on the quality of HHR in the MD as well as other similar regions in South-East Asia. Instead, most drinking water quality investigations in this region focus on ground water due to the well-known presence of pollutants (Buschmann *et al.*, 2008). Research on rainwater quality mainly focuses on the perception of drinking water sources (Herbst *et al.*, 2009) and knowledge about HHR practices and attitudes by residents (Özdemir *et al.*, 2011). The objectives of this study were: i) to investigate the quality of household harvested rainwater in the Mekong Delta for general parameters, nutrients, heavy metals and microbial indicator bacteria and compare observed concentrations with (inter)national guidelines with respect to drinking water; ii) to identify the role of local (roof type, storage system, storage duration) and spatial (proximity to industry, main roads, coastline) specific conditions on the quality of household harvested rainwater in the region, iii) to assess the potential influence of household specific conditions on the quality of household stored rainwater and iv) to provide recommendations aimed at improving the quality of harvested rainwater as a safe drinking water resource. The outcome of this study will be useful for policy makers in Vietnam as well as other similar regions in South East Asia to draw conclusions about the use and required treatment of rainwater as a potential drinking water source for the rural areas and for the use at water supply stations in urban areas.

3.2. Materials and Methods

3.2.1 Study sites

This study was carried out in three provinces of the MD, i.e. Can Tho, Hau Giang and Soc Trang (Fig. 7).

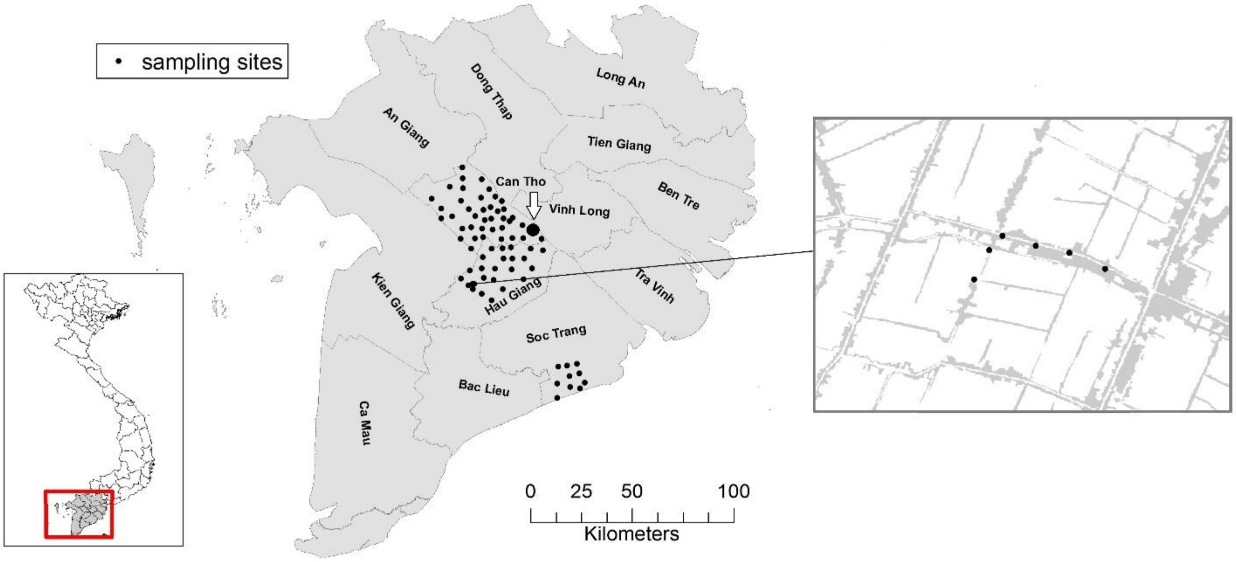


Figure 7 – Visualization of sampling locations in Can Tho, Hau Giang and Soc Trang provinces. The small scale study site is highlighted (southern location in Hau Giang) and shown by a detailed map. Main industrial zone in Can Tho City is shown as a larger black dot.

Characteristic land-use types in Can Tho and Hau Giang provinces consisted mainly of rice fields (40%), orchards (13%) and fresh water aquaculture (0.5%) combined with open to dense urbanized and industrial agglomerations (German Aerospace Center, 2011), whereas in the Soc Trang province, shrimp farming was the main observed land-use system. Most people in rural areas live along the numerous canals and rivers. The climate in this tropical region is influenced by the southwest monsoon which creates dry and wet seasons. The wet season is generally from May to October with an annual average rainfall of 1,660 mm defined by 23 years of measurements (Delta Alliance, 2011). During the dry season rainfall events are scarce or completely absent. A survey of 542 household (HH) interviews in the study sites (own unpublished data) revealed that almost 60% of the HHs are using rainwater as a drinking water source; however, the use differed considerably within the region. Some villages preferred groundwater or even surface water to rainwater, while other villages only used rainwater as their source of drinking water. Households that collect rainwater usually use metal gutters to collect rainwater from roofs. The gutters transport the collected rainwater to storage basins (typically clay jars or concrete tanks) from which it is used with or without treatment.

3.2.2 Sampling and analytical methods

Samples of household-harvested rainwater were collected in 2012 from July to October. A total of 72 locations were selected at 5 kilometer intervals to achieve good spatial representation. Measurement locations were pre-defined ahead of sampling and localized by GPS in the field (Garmin ETrex, Olathe, KS, USA). After arrival at the pre-defined location, households were screened for drinking water sources. The first household identified using rainwater for consumption near the pre-defined location was selected for analysis regardless of roof type and spatial conditions in order to get insight into actual variation of household and spatial specific conditions. The exact location of sample collection was recorded. Ten samples were collected in Soc Trang province whereas 62 samples were collected in Can Tho and Hau Giang provinces. In addition, a small case study of 6 neighboring households was undertaken in the rural areas of Hau Giang Province to investigate the potential influences of household specific conditions such as behavioral aspects. In this area, most households stored rainwater for drinking since groundwater was unpopular due to its strong saline taste. Within a small area, spatial conditions did not differ among the households. All the selected locations were sampled once.

Water samples were collected directly from the storage basins to represent the water use by local people. Samples were analyzed for general parameters (Electrical Conductivity, pH and turbidity), nutrients: nitrate (NO_3), nitrite (NO_2), ortho-phosphate (o-PO_4) and ammonium (NH_4), Chemical Oxygen Demand (COD), microbial indicators (*E. coli* and total coliforms), and metal(loid)s including total arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb) and zinc (Zn). The samples from the small scale study area were analyzed for microbial indicators and metal(loid)s only. 100 ml polyethylene (PE) bottles were used to store water for COD, turbidity and nutrients analysis. 50 ml PE bottles were filled with water samples and acidified with 1% nitric acid (Purity 65%, Merck Millipore, Billerica, MA, USA) for (heavy) metal analysis. Sterilized 100 ml glass bottles were used to store water for microbial analysis. All samples were cooled with ice during transportation and delivered to the laboratory within 8 hours of sampling.

Conductivity and pH was measured in-situ by the instrument WTW Multi 340i (Weilheim, Germany). For nutrient and COD analysis, all samples were stored at 5 °C, pre-treated by syringe filters (0.45 µm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 hours. COD was analyzed with the reactor digestion method for low range COD, while NH_4 concentrations were determined photometrically by the low range AmVer™ Salicylate Test 'N Tube™ method (Hach, Loveland, CO, USA). NO_3, NO_2 and o-PO_4 were measured using Merck Spectroquant ® cell tests at the lowest concentration range (Merck Millipore, Billerica, MA, USA). The turbidity of unfiltered water was determined using HACH Turbidimeter (Loveland, CO, USA). Samples for microbial analysis were treated within 10 hours of sampling under sterile conditions by plating 1 ml of sample water on 3M™ petrifilm™ coliforms count plates (3M, St. Paul, MN, USA) with replication (n=2). *E. coli* and other coliform colonies were counted 24±4 hours after incubation at 37ºC. Samples for metal analysis were stored in a fridge at 5°C and analyzed within three months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA).

3.2.3 Local and spatial conditions

Local specific conditions were assessed through household interviews. The interviews were structured with open questions including the type of roof that was used for rainwater harvesting, applied storage system and duration, the application of treatments before consumption, the separation of first flush rainwater and their judgment about the quality of harvested rainwater for drinking. Interviewees were also asked to show how they collect rainwater from their storage basin to get insight into household specific aspects such as behavioral patterns.

The spatial conditions considered in this study included the distance to (i) main roads, (ii) an intensive industrial/urbanized agglomeration in Can Tho City and (iii) the sea. The distance from each selected measurement location to main roads, industrial zone and the coastline was calculated by applying spatial-join techniques in ArcGIS 10.

3.2.4 Statistical analysis

All statistical tests were carried out with SPSS version 20.0. Non-parametric statistical tests were applied to account for the relative small number of samples, the presences of outliers and the lack of normal distribution (tested by Shapiro-Wilk test). The Kruskal-Wallis test was used to find significant differences between the water quality of different roof types. In case significant differences were detected, the Mann-Whitney-Wilcoxon test was applied to investigate differences within the groups and were visualised using box-and-whisker diagrams. Correlations between spatial conditions with HHR were assessed with Spearman's rho test. Weight of evidence was indicated by three different p-values (moderate: $0.05 < p \leq 0.10$; strong: $0.01 < p \leq 0.05$; very strong: $p \leq 0.01$).

3.3 Results

3.3.1 Household interviews

During sample collection, three different roof types were observed: concrete/asbestos tiles, thatch, and galvanized metal sheets (24%, 13% and 63% of the locations respectively). All selected households used gutters for collection of rainwater to storage basins. 85% of households using rainwater for drinking, stored water in clay or concrete jars which were usually covered by a metal, wood or stone plate. The estimated capacity of a jar is around 500 – 1,000 liters although most households had several jars to increase the overall storage capacity. The amount of jars per household varied between 1 and >10 depending on the available space, income and personal demand. The other 15% of households used concrete tanks with a storage capacity of several thousand liters. Usually, households with water tanks had one storage basin. Nevertheless, samples were always collected from the storage basin that was used for drinking at the moment of sampling. Households indicated the use of rainwater for drinking due to positively judged parameters such as color and smell in comparison with other potential sources such as ground and surface water. However, people showed hesitation in drinking rainwater when they were located close to main provincial or national roads and/or large urbanized/industrialized agglomerations. Only respondents having houses with thatched roofs mentioned a light-yellow color of harvested rainwater but did not consider this as a health risk. In 53% of surveyed households, the harvested rain water was consumed without any treatment while 7% of the respondents claimed to treat rainwater only occasionally. The other 40% indicated that they boil the water prior to drinking. Most households (97%) indicated that they divert first flush rainwater from storage basins. Typically, people claimed to start collecting rainwater after the first five minutes of rainfall. Residents indicated that they collect water from the storage basins directly, e.g. using buckets.

The six households at the small case study area that harvested rainwater for drinking all had metallic roofs and transferred rainwater via metallic gutters to concrete jars. All of the investigated jars contained covers to prevent intrusion of dust.

3.3.2 Household harvested rainwater quality

The HHR quality results (Table 5) are provided as median values and ranges since data do not follow a normal distribution.

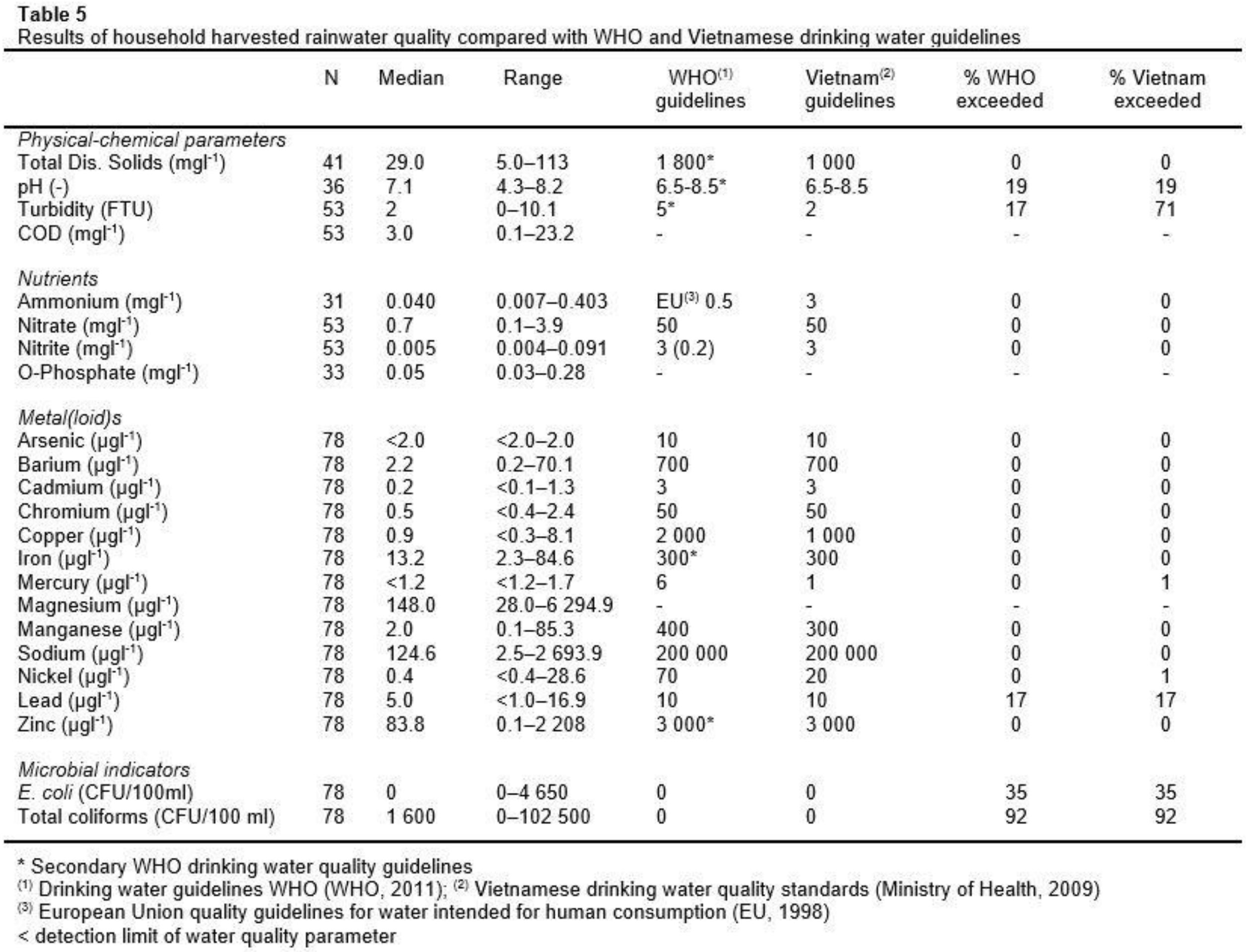


Table 5

Results of household harvested rainwater quality compared with WHO and Vietnamese drinking water guidelines

	N	Median	Range	WHO$^{(1)}$ guidelines	Vietnam$^{(2)}$ guidelines	% WHO exceeded	% Vietnam exceeded
Physical-chemical parameters							
Total Dis. Solids (mgl^{-1})	41	29.0	5.0–113	1 800*	1 000	0	0
pH (-)	36	7.1	4.3–8.2	6.5-8.5*	6.5-8.5	19	19
Turbidity (FTU)	53	2	0–10.1	5*	2	17	71
COD (mgl^{-1})	53	3.0	0.1–23.2	-	-	-	-
Nutrients							
Ammonium (mgl^{-1})	31	0.040	0.007–0.403	EU$^{(3)}$ 0.5	3	0	0
Nitrate (mgl^{-1})	53	0.7	0.1–3.9	50	50	0	0
Nitrite (mgl^{-1})	53	0.005	0.004–0.091	3 (0.2)	3	0	0
O-Phosphate (mgl^{-1})	33	0.05	0.03–0.28	-	-	-	-
Metal(loid)s							
Arsenic (µgl^{-1})	78	<2.0	<2.0–2.0	10	10	0	0
Barium (µgl^{-1})	78	2.2	0.2–70.1	700	700	0	0
Cadmium (µgl^{-1})	78	0.2	<0.1–1.3	3	3	0	0
Chromium (µgl^{-1})	78	0.5	<0.4–2.4	50	50	0	0
Copper (µgl^{-1})	78	0.9	<0.3–8.1	2 000	1 000	0	0
Iron (µgl^{-1})	78	13.2	2.3–84.6	300*	300	0	0
Mercury (µgl^{-1})	78	<1.2	<1.2–1.7	6	1	0	1
Magnesium (µgl^{-1})	78	148.0	28.0–6 294.9	-	-	-	-
Manganese (µgl^{-1})	78	2.0	0.1–85.3	400	300	0	0
Sodium (µgl^{-1})	78	124.6	2.5–2 693.9	200 000	200 000	0	0
Nickel (µgl^{-1})	78	0.4	<0.4–28.6	70	20	0	1
Lead (µgl^{-1})	78	5.0	<1.0–16.9	10	10	17	17
Zinc (µgl^{-1})	78	83.8	0.1–2 208	3 000*	3 000	0	0
Microbial indicators							
E. coli (CFU/100ml)	78	0	0–4 650	0	0	35	35
Total coliforms (CFU/100 ml)	78	1 600	0–102 500	0	0	92	92

* Secondary WHO drinking water quality guidelines

$^{(1)}$ Drinking water guidelines WHO (WHO, 2011); $^{(2)}$ Vietnamese drinking water quality standards (Ministry of Health, 2009)

$^{(3)}$ European Union quality guidelines for water intended for human consumption (EU, 1998)

< detection limit of water quality parameter

Water quality parameters are compared with WHO drinking water guidelines and the more stringent Vietnamese national drinking water guidelines. Recorded pH values varied between 4.3 and 8.2 although in 42% of the samples, pH was lower than 7.0 and in 19%, below 6.5. Turbidity exceeded the guidelines for 71% versus 17% of the samples for Vietnamese and WHO drinking water standards, respectively.

Nutrient concentrations were low and did not exceed any of the guidelines. Nevertheless, weak but significant relationships between o-PO_4 and Mg and Zn were observed (Table 6). At most measurement locations, heavy metals were detected only at trace levels, while Pb, Fe and Zn occurred with median concentrations of 5.0, 13.2 and 83.8 µgl^{-1}, respectively. In one sample, Ni (28.6 µgl^{-1}) and Hg (1.7 µgl^{-1}) exceeded the Vietnamese drinking water standards. Zn was found in high concentrations at many locations, although drinking water guidelines were not exceeded. Pb was detected in many samples and exceeded water quality standards for 17% of the samples. The earth metals Mg and Na were found in larger concentrations (median 148.0 µgl^{-1} and 124.6 µgl^{-1}); however, these substances are relatively harmless with respect to human health. Microbial pollution, on the other hand, was detected in a large number of samples and exceeded guideline values in 35% and 92% of the samples for *E. coli* and total coliforms, respectively. Weak but significant inverse correlations between total coliforms amount with Cr and Ni were also found (Table 6).

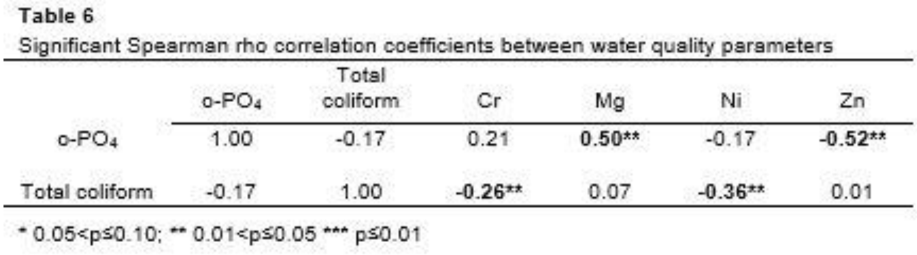


Table 6
Significant Spearman rho correlation coefficients between water quality parameters

	o-PO$_4$	Total coliform	Cr	Mg	Ni	Zn
o-PO$_4$	1.00	-0.17	0.21	**0.50****	-0.17	**-0.52****
Total coliform	-0.17	1.00	**-0.26****	0.07	**-0.36****	0.01

* 0.05<p≤0.10; ** 0.01<p≤0.05 *** p≤0.01

The quality of harvested rainwater in the small case study site is presented in Table 7. Although local and spatial conditions were similar, the tested samples showed a high degree of variability for the tested metals and for microbial pollution.

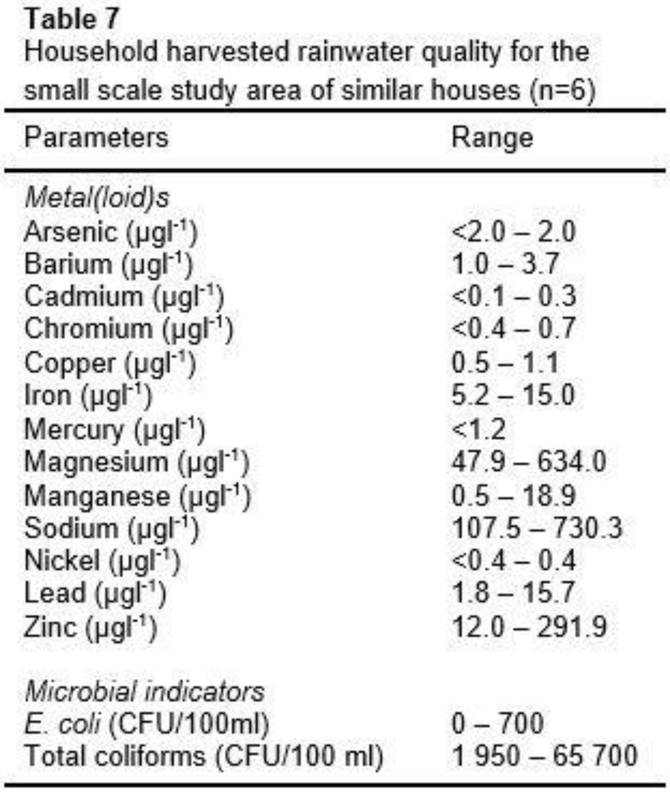


Table 7
Household harvested rainwater quality for the small scale study area of similar houses (n=6)

Parameters	Range
Metal(loid)s	
Arsenic (µgl^{-1})	<2.0 – 2.0
Barium (µgl^{-1})	1.0 – 3.7
Cadmium (µgl^{-1})	<0.1 – 0.3
Chromium (µgl^{-1})	<0.4 – 0.7
Copper (µgl^{-1})	0.5 – 1.1
Iron (µgl^{-1})	5.2 – 15.0
Mercury (µgl^{-1})	<1.2
Magnesium (µgl^{-1})	47.9 – 634.0
Manganese (µgl^{-1})	0.5 – 18.9
Sodium (µgl^{-1})	107.5 – 730.3
Nickel (µgl^{-1})	<0.4 – 0.4
Lead (µgl^{-1})	1.8 – 15.7
Zinc (µgl^{-1})	12.0 – 291.9
Microbial indicators	
E. coli (CFU/100ml)	0 – 700
Total coliforms (CFU/100 ml)	1 950 – 65 700

3.3.3 Influence of local and spatial conditions

The concentrations of substances in HHR that were significantly influenced by roof types are shown in Fig. 8.

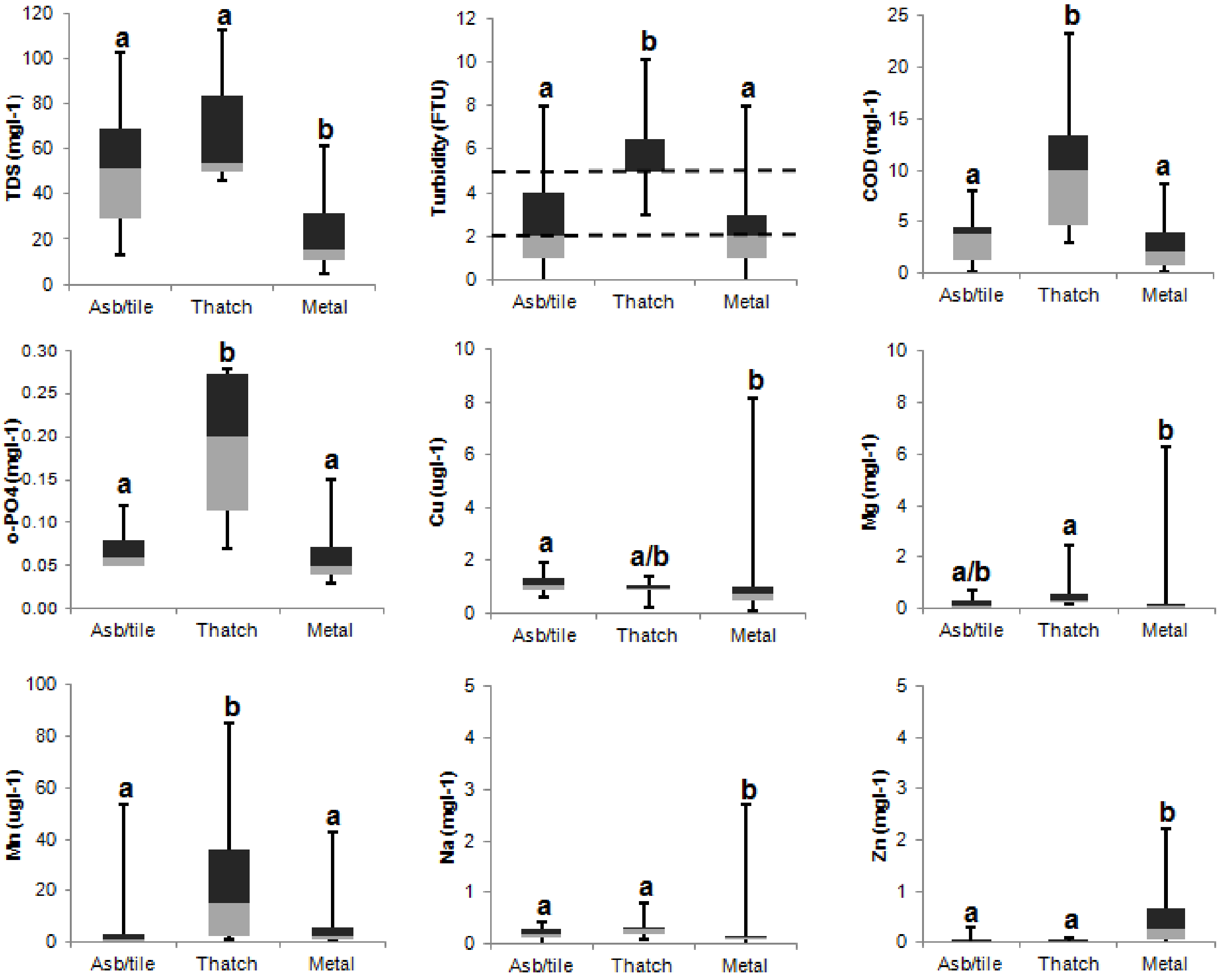


Figure 8 – Differences between Household Harvested Rainwater quality and roof types in the Mekong Delta. Roof types consist of (1) asbestos and concrete tiles, (2) thatch cover and (3) galvanized metal sheets. The bars show from bottom to top: minimum – 25 percentile – median – 75 percentile – maximum concentrations. The letters "a" and "b" above the bars indicate significantly different concentrations between the roof types at the $p<0.05$ level; a/b indicates no significant difference with any other roof type. The dashed lines for turbidity indicate the Vietnamese (2 FTU) and WHO (5 FTU) drinking water guidelines.

The concentrations of turbidity, COD, o-PO_4 and Mn were significantly higher in harvested rainwater from thatch roofs in comparison with the other investigated roof types. Moreover, turbidity concentrations in HHR from thatch roofs exceeded drinking water guidelines in most cases. The highest Zn concentrations were detected in harvested rainwater from metallic roof types. An opposite pattern is visible for the concentrations of TDS, Cu, Mg, and Na.

For most substances, the type of storage vessel did not influence the quality of HHR. Differences were only visible for NH_4 and NO_2 concentrations (Fig. 9) that showed significantly higher amounts in HHR stored in tanks compared with storage in jars. However, regardless of storage system, guideline values for these substances were not exceeded.

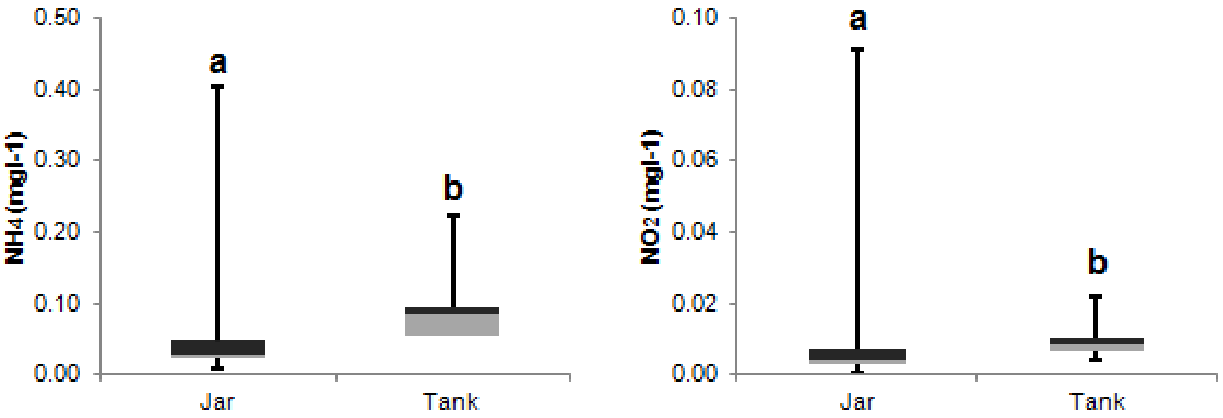


Figure 9 – The concentrations of NH_4 and NO_2 in HHR stored in jars (n = 61) versus tanks (n = 11). The letters “a” and “b” above the bars indicate significantly different concentrations between storage basins at the $p<0.05$ level.

The relationship between the distance of an HHR to an industrial agglomeration, main roads, coastline and storage duration with the water quality parameters are shown in Table 8.

Table 8

Spearman rho correlation coefficients for relationships between water quality parameters and spatial conditions and storage duration

	Distances			
	Industry	Main roads	Coastline	Storage duration
TDS	0.07	-0.04	-0.52***	0.02
pH	-0.35**	-0.03	0.33*	-0.24
Turbidity	0.19	0.00	-0.36**	0.24
COD	0.27*	0.02	-0.35**	0.15
Ammonium	-0.16	-0.27	0.11	0.00
Nitrate	0.00	0.19	-0.31**	-0.12
Nitrite	-0.02	0.10	0.07	-0.12
o-phosphate	0.18	0.24	-0.02	-0.18
Arsenic	-0.05	0.09	0.10	-0.06
Barium	-0.26**	-0.18	0.11	0.00
Cadmium	-0.05	0.00	0.14	-0.19
Chromium	0.00	-0.08	-0.22*	0.09
Cupper	0.22*	-0.16	-0.12	0.08
Iron	0.02	-0.13	-0.12	0.08
Mercury	0.12	-0.07	-0.09	0.21
Magnesium	0.15	-0.12	-0.27**	0.16
Manganese	0.08	-0.15	-0.08	0.01
Sodium	0.27**	0.09	-0.19*	0.20
Nickel	-0.12	-0.08	0.03	0.15
Lead	0.04	-0.19	-0.12	0.11
Zinc	-0.28**	-0.18	0.30**	-0.06
E. coli	0.12	-0.02	0.06	-0.08
Total coli.	0.04	0.01	0.02	0.11

* $0.05<p\leq0.10$; ** $0.01<p\leq0.05$ *** $p\leq0.01$

Ba and Zn concentrations as well as pH levels were inversely correlated with the distance to the industrial zone in Can Tho province indicating highest values close to the industrial zone. The reverse was true for COD and the concentrations of Cu and Na which tended to be lower close to the industrial zone. The presence of main roads did not show any significant effect on HHR quality. Concentrations of TDS, turbidity, COD, NO_3, Mg and Na show moderate relationships with distance to the sea, indicating that concentrations of these substances were highest at sampling locations close to the coastline. The opposite was observed for Zn concentrations and pH values, which were highest at inland locations. The duration of water storage did not influence the quality of HHR.

3.4 Discussion

3.4.1 Effects of local conditions on HHR quality

Turbidity was significantly higher ($p<0.05$) in rainwater harvested from thatched roofs compared with other roof types. However, in the MD, even turbidity of HHR from thatched roof samples were lower in comparison with other studies that reported levels between 5 and 35 FTU on shingle and metal roofs (Mendez *et al.*, 2011). Nevertheless, the observed turbidity in harvested rainwater in this study may imply a notable concern for drinking water quality since chlorination efficiency is reduced at concentrations >5 FTU (LeChevallier *et al.*, 1981). Similar patterns of significantly higher concentrations in HHR from thatched roofs were visible for COD and o-PO_4 and Mn. However, the concentrations of COD and o-PO_4 were also generally low compared with other studies (e.g. 44 – 120 mgl^{-1} for COD (Villarreal *et al.,* 2005) and up to 1.52 mgl^{-1} for o-PO_4 (Lee *et al.*, 2010)), while the observed concentrations of Mn were in line with that of Olabanji and Adeniyi (2005) who investigated rainwater quality in Nigeria. In summary, thatch roofs were shown to cause more pollution in harvested rainwater when compared with other roof types. However, the detected concentrations were typically lower than reported concentrations in other studies. A possible explanation is that sampling was conducted during the rainy season, so that the frequent and partially heavy rain events decreased the risk for the accumulation of potential contaminants such as leaves, sand, dust, bird excrement etc. on the roofs. Strong rains in the rainy season are unique for tropical regions subjected to monsoons and could therefore explain different findings with studies in non-monsoonal regions. This was supported by a study of harvested rainwater in Bangladesh that also showed generally lower concentrations for some substances such as COD in comparison with non-monsoonal regions (Islam *et al.*, 2010). As expected, highest Zn concentrations were detected in galvanized metal roof types ($p_{asb/tile}$ and p_{thatch} both < 0.01). The concentration of this metal in harvested rainwater was generally high due to leaching from zinc galvanized roof types which does not occur with the other observed roof types in the MD. These results contradict those of Lee *et al.* (2012) who investigated metal levels in harvested rainwater from a variety of roof types as well. Lee *et al.* (2012) showed that harvested rainwater from roof types such as wood shingles and concrete tiles had highest concentrations of Zn compared with all other roof types including galvanized sheets. However, it was also found that this was not the case for first-flush rainwater that showed highest concentrations of Zn from metal roofs. Therefore, the high Zn concentrations in stored harvested rainwater from metal roofs in our study, suggest that first-flush separation is not performed optimally in the MD. Although concentrations of Cu were relatively small in HHR, significantly lower concentrations were detected in water collected from metal roofs compared to samples from asbestos/tile roofs ($p < 0.01$). However, the observed concentrations of Cu in HHR were typically lower than reported in other studies (Lee *et al.*, 2012), which is in line with the observation that Cu is not observed visually around roofs and gutters in the MD.

The concentrations of Mg in HHR in metal roofs show lower concentrations compared with thatched roofs ($p < 0.01$). However, regardless of roof type this substance was observed in almost all samples. These concentrations may not be mainly caused by leaching from roofs but instead by leaching from storage systems. The main components of concrete which is used for storage systems (tanks and jars) are Mg and o-PO_4. These substances dissolve since fresh rainwater is usually slightly acid. During storage, the pH will gradually increase as a result of the leaching of these substances. Higher pH values were indeed observed in this study as well as in a study in South Korea that investigated the pH of stored rainwater (Lee *et al.*, 2010). The gradual leaching of these substances from storage basins is also confirmed by Meera and Mansoor Ahammed (2006) and Villarreal *et al.* (2005) who observed increasing pH values during storage of water. Nevertheless, there were no significant correlations between pH, Mg, o-PO_4 and other water quality parameters with storage duration in this study which suggests that people are not truly aware of the storage duration of the rainwater. People usually harvest rainwater from different rainfall events which makes an accurate estimation of storage duration difficult. Both asbestos/tile and thatch roofs show slightly higher concentrations of Na compared with metal roofs ($p_{asb/tile} < 0.01$; $p_{thatch} < 0.01$), except for one outlier (2.7 mgl^{-1}). In summary, most of the substances (except for Zn) showed lowest concentration in HHR from metal roofs which explains the significantly lower concentrations of TDS in comparison with the other roof types ($p_{thatch} < 0.05$; $p_{Asb/tile} < 0.01$).

The slightly higher observed concentrations of NH_4 and NO_2 in stored rainwater in tanks compared with jars could be explained by accumulation of organic compounds in tanks and longer storage duration. First flush is generally not performed since most of the tanks are directly connected to roofs. Moreover, the storage duration in tanks is expected to be longer compared with jars. These factors might lead to a stronger degradation of organic compounds to ammonium and nitrates compared with jars.

3.4.2 Effects of spatial conditions on HHR quality

Based on the literature, a strong relationship between the presence of industrial activities and harvested rainwater quality was expected for heavy metals such as Pb, Cu and Zn (Thomas and Greene, 1993; Chang *et al.*, 2004). Except for a weak, but nevertheless significant, correlation with Zn this pattern was not observed for these substances in the MD. Instead Ba and pH levels were inversely correlated with the distance to the industrial zone in Can Tho province indicating highest detected values close to this industrial area. The higher concentrations of Ba near an industrial zone may be the result of burning fossil fuels, in particular coal, during production processes of industrial activities (Jickells *et al.*,1992). Nevertheless, water quality guidelines were not exceeded for heavy metals near industrial locations. Surprisingly, the presence of main roads did not show any significant effect on HHR quality. The lack of correlation could be the result of a widely developed secondary road network present along almost every canal in the region. Therefore, emissions by traffic as well as air-borne dust, which could be potential pollutants, are widely spread over the region. The relationship between distance to coastline and concentration of Mg and Na may be the result of settling of sea salt which is expected to be strongest near coastal regions. However, the other significant relationships between water quality parameters and coastline could be explained by the differences in the preferred roof type among the study sites. Most houses near the coastline have asbestos and thatch roofs that falsely suggest significant correlations for TDS, turbidity, COD and NO_3. A similar pattern is visible for the detected correlation of Zn with the coastline and the correlation of Na with distances to industrial areas.

3.4.3 Household specific aspects

Microbial pollution of HHR poses a serious risk to human health in the MD since contamination with fecal indicator bacteria was observed in a majority of households. Moreover, the majority of residents have the perception that the quality of HRR is good and safe for dinking. Thus, only a few people apply treatments to HHR before consumption, which is in line with other studies (Özdemir *et al.*, 2011). The prevalence of microbial contamination in HHR in the MD is generally higher than reported elsewhere (92% in the MD versus up to 63% in other studies (Ahmed *et al.,* 2008)). Moreover, the number of total coliforms in the MD samples is 10 – 100 times higher compared with these studies. Based on the literature, a positive correlation was expected between certain roof types and coliforms especially for thatched roofs (Lee *et al.*, 2012). However, neither *E. coli* nor total coliform amounts correlated with any of the studied roof types and or other spatial / local specific parameters. Most probably, the extent of microbial pollution is influenced by a combination of several other household specific aspects including storage cover type, storage place (inside or outside, distance to sanitary facilities, etc.), differences in fecal deposition on roofs due to presence or absence of overhanging vegetation, human handling aspects and lack of hygiene perspectives (Herbst *et al.*, 2009), as well as the frequency of cleaning of storage basins, first flush separation and the rate of water use. Another possible reason for the observed large variations is the mixing of water from different sources since the same vessels are used to store surface- and groundwater in the dry season. Thus, at the beginning of the rainy season, when residents start to harvest rain water, the vessels might still contain high loads of microbes and metals as a residue from the former source of water. This is especially true for households which lack financial resources to invest in storage capacity such as jars and tanks. This could also explain the higher observed concentrations of Ni and Hg detected in one sample.

These factors could result in the observed high variability in the occurrence of coliforms in HHR and is confirmed by the small scale study area that showed very large variations in the presence of coliforms in the HHR at neighboring households. Although spatial and local conditions were similar in this case study, household specific conditions such as first flush separation, storage area, human-handling aspects etc. were not assessed in detail and could possibly vary among the households. Therefore, at this stage we can only demonstrate the importance of these parameters and highlight the need for more research on the role of these household conditions to assess its impact on fecal contamination in HHR. Although most heavy metals occurred in trace amounts, the inverse correlation between Ni and Cr with total coliforms indicates its bacteriostatic effects.

Despite occurring in the majority of the samples, significant correlation of Pb between local and spatial conditions is lacking. Also, the fuel used in the MD is unleaded (UNEP, 2009). Plumbing systems on gutters and roofs, which are a frequent source for contaminants in drinking water (Al-Mudhaf *et al.*, 2012), could be a major source of Pb contamination in harvested rainwater. Furthermore, the burning of household waste is a common practice in the MD; this could result in background Pb concentrations in air, which could be flushed out by rainfall. Even when first flush separation is applied effectively, Pb could be found a few days after a rainfall event in storage tanks according to research in Australia (Magyar *et al.*, 2008). This could be another explanation for the detected traces of other heavy metals in HHR but more investigations are required on this issue.

This study found severe contamination of HHR with microbial pathogens and lead. However, alternative drinking water sources in the MD are found to be even more polluted. Surface water in the MD for example is heavily contaminated with pathogens. The concentrations of both *E. coli* and total coliform in surface water were found to be 100 to 1000 fold higher when compared with harvested rainwater quality in this study (Isobe *et al.* 2004). Groundwater, which is another main drinking water source in the region, is found to be heavily contaminated with metals, and often exceeds drinking water guidelines for As, Mn and Fe (Hoang, *et al.* 2010), which did not present any problem in HHR. However, the problem with harvested rainwater in the MD is that most people perceive this source to be clean which is different to that of the other sources and thus, in many cases, do not apply treatment before consumption. Therefore, the main challenge for decision makers is to focus on raising awareness of the fecal contamination of stored rainwater which is mainly influenced by household-specific aspects. Inhabitants of the MD should be encouraged to boil and/or treat water chemically before consumption even if they perceive the source to be safe. Practical solutions such as application of taps on storage systems and permanently covering the basins could further reduce microbial pollution of stored water. In addition, household waste collection systems should be organized to reduce the burning of waste that leads to hazardous emissions such as heavy metals. Based on the household specific conditions that most probably cause this contamination, improvements should focus on educational measures such as improved hygiene practices, proper coverage practices, and the prevention of mixing different water sources.

3.5 Conclusions

Rainwater is a main drinking water source in the MD due to the lack of safe water supplies, especially in rural areas. Moreover, rainwater is considered a safe source due to positively characterized features such as color, taste and smell. However, local (roof types, storage system and duration) and spatial conditions (proximity to roads, industry, coastline) are expected to lead to contamination of this drinking water sources.

This study shows that thatched roofs caused higher contamination by organic substances and Mn in comparison with asbestos/concrete tile and galvanized metal roofs, while Zn concentrations were highest in rainwater harvested from galvanized roofs. Although most concentrations remained below drinking water guidelines and are generally lower compared with other harvested rainwater studies world-wide, the detected levels of turbidity would likely lead to problems during chlorination disinfection especially for rainwater harvested from thatch roofs. Rainwater stored in tanks showed small but nevertheless significantly higher concentrations of NH_4 and NO_2 compared with rainwater stored in jars. Storage duration did not significantly influence the quality of stored rainwater, although most households are probably not fully aware of the storage duration of their stored rainwater. The analysis of spatial conditions revealed that the quality of harvested rainwater is not severely influenced by the proximity of industrial zones and main roads although local people are hesitant about using rainwater for drinking when they are located close to these types of infrastructure. Only Ba and Zn concentrations and pH values near an industrial zone were found to be elevated; however, drinking water guidelines were still not exceeded. Na and Mg concentrations showed highest values at households near coastlines due to sea salt deposition from the air. However, the raised concentrations of Mg could also be explained by the leaching of cement-based components of storage systems due to the slight acidity of rainwater. This was confirmed by the strong correlation between the concentrations of Mg and o-PO_4 which are main components in cement. Nevertheless, the leaching of these substances does not imply a health risk. Instead, the most severe health risks associated with the consumption of HHR are caused by fecal contamination and Pb which were frequently detected in elevated concentrations. Fecal and Pb contamination is not explained by local and/or spatial parameters but most likely by a variety of household-specific conditions like storage, coverage, handling, and other conditions. Pb pollution likely originates from plumbing systems and the burning of household waste. However, more research is required to determine the impact of combined conditions on the quality of harvested rainwater. Other potential water sources like surface- and groundwater are found to be heavily contaminated by a variety of organic and microbial pollutants as well as metal(oid)s like arsenic. In summary, based on our investigated water quality parameters, harvested rainwater is one of the best drinking water sources in the region if measures are taken to ensure appropriate harvesting, handling, and treatment prior to consumption. Thus, educational programs would likely help maximize the safety of harvested rainwater and raise awareness about the necessity to boil the water before consuming it.

4. Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam

Abstract

Surface water pollution in the Vietnamese Mekong Delta (MD) could threaten human, animal and ecosystem health given the fact that this water source is intensively used for drinking, irrigation and domestic services. We therefore determined the levels of pollution by organic pollutants, salts, metals and microbial indicators by (bi)monthly monitoring of canals between November 2011 – July 2012 at 32 sampling locations, representing a fresh and a saline/brackish environment. The results were compared with national water quality guidelines, between the studied regions and with water quality data from main waterways. Key factors explaining the observed levels of pollution in surface water were identified through Principal Component Analysis (PCA). Temporal variations due to tidal regime and seasonality were also assessed. Based on regression models, the spatial variability of five water quality parameters was visualized using GIS based maps. Results indicate that pH (max. 8.6), turbidity (max. 461 FTU), maximum concentrations of ammonium (14.7 mgL^{-1}), arsenic (44.1 µgL^{-1}), barium (157.5 µgL^{-1}) , chromium (84.7 µgL^{-1},) mercury (45.5 µgL^{-1}), manganese (1659.7 µgL^{-1}), aluminum (14.5 mgL^{-1}), iron (17.0 mgL^{-1}) and the number of *E. coli* (87,000 CFU 100 mL^{-1}) and total coliforms (2,500,000 CFU 100 mL^{-1}) in canals exceed the thresholds set by Vietnamese quality guidelines for drinking and domestic purposes. The PCA analysis showed that i) urbanization; ii) metal leaching from soils; iii) aquaculture and iv) the tidal regime explain 85% of the variance of surface water quality attributes. Significant differences in water quality were found due to daily tidal regime and as a result of seasonality. Surface water quality maps for dissolved oxygen, ammonium, ortho-phosphate, manganese and total coliforms were developed to highlight hot-spot areas of pollution. The results of this study can assist policy makers in developing water management strategies and drinking water companies to select optimum water extraction locations.

4.1 Introduction

In the Mekong Delta (MD), Vietnam and in other coastal regions of Southeast Asia, people rely on surface water not only for the irrigation of crops, aquaculture and the transportation of goods, but also for daily domestic uses including for drinking. Poor water quality and inadequate pre-treatment of surface water before use can lead to serious health risks and may be a contributing factor to the high mortality rate of 8.5% of all deaths due to diarrhea in Southeast Asia (WHO, 2013b). It is widely known that the quality of surface water in the region is threatened by a variety of pollutants from both natural and anthropogenic sources. The surface water quality in the MD is therefore regularly monitored by the provincial authorities (DONRE), by the Mekong River Commission, but also by a number of time-bound projects, covering diverse pollutants (Sebesvari *et al.*, 2012). The results of these studies show for example that pesticide residues in the aquatic environment can lead to a chronic exposure of humans and aquatic organisms (Toan *et al.*, 2013). Due to the low topographical elevation of the MD, saline water intrusion is another water quality concern affecting especially rice production in coastal areas (Kotera *et al.*, 2008). An assessment of microbial indicators of fecal pollution revealed high loads of *E. coli* (10^2 - 10^7 CFU 100 ml^{-1}) and total coliforms (10^3 – 10^7 CFU 100 ml^{-1}) in many surface waters (Isobe *et al.*, 2004). However, the concentrations of various heavy metals, including cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb), investigated in main waterways and coastal zones, were low compared to other catchment areas in the world (Cenci and Martin, 2004). The Mekong River Commission (MRC) also investigated water quality of the Mekong River in Laos, Thailand, Cambodia and Vietnam, and concluded at most observation points, that the water quality was moderate to good with respect to nutrients and metals. However, salinity and especially acidity levels were found to be problematic within the Delta (MRC, 2008).

Most investigations on surface water focus on acid sulphate soils (ASS), covering 40% of the total agricultural surface area in the MD (Guong and Hoa, 2012). The strong acidity in these soils increases the mobility of toxic elements, potentially affecting crop production, aquatic organisms and drinking water sources (Ljung *et al.*, 2009). In the Plain of Reeds of the MD, pH values of 3.5 were associated with elevated concentrations of aluminum (Al) and iron (Fe) in the early wet season (Tin and Wilander, 1995; Husson *et al.*, 2000). The observed Al concentrations of >100 mg L^{-1} exceed the toxicity levels for fish and plant roots (Minh *et al.*, 1997). Besides Al and Fe, also other metals like Cd, Cu, Ni, Mn and Zn are present in higher concentrations in surface water then in areas with alluvial soils (Hoa *et al.*, 2007).

Another important source of water contamination is aquaculture, leading to high levels of COD, BOD and nutrients in water as a result of the applied fish food (Anh *et al.*, 2010). Shrimp farming is a main activity in the coastal areas (e.g. in Soc Trang and Ca Mau provinces) leading to low concentrations of dissolved oxygen, while suspended solid concentrations are consistently high (Johnston *et al.*, 2002). Furthermore, the effects of urbanization on surface water contamination are well recognized. Two independent studies in Ohio, USA showed clear correlations between electrical conductivity and concentrations of nutrients with urban land-uses (Wang and Yin, 1997; Tong and Chen, 2002). Similar findings were reported from urbanized areas in China (Wang *et al.*, 2007), and a study conducted in Shanghai revealed that 94% of the variability in water quality was explained by industrial/domestic urban land uses (Ren *et al.*, 2003). There are no comparable studies in the MD except for one report by Quyen *et al.* (1995) who concluded that both urbanization and industrialization are becoming serious threats to water quality.

Besides these anthropogenic and soil type-related sources of pollutants, climatic and seasonal effects are also found to influence water quality. Thus in the lower Mekong River, hydrological and climatological factors (precipitation, flow discharge, mean water level and air temperature) were strongly correlated with COD and dissolved oxygen concentrations in surface water (Prathumratana *et al.*, 2008). Studies in Florida (USA), Spain and northern China revealed seasonal differences in water quality parameters (Ouyang *et al.*, 2006; Vega *et al.*, 1998; Chen *et al.*, 2005). Similar studies in the MD are limited to a study by Stärz (2012) who investigated surface water quality in two districts of Can Tho province.

While many water quality studies have been conducted in the MD, most focused on either point sources and soil types effects or investigated the surface water quality in main waterways. The lower order canals are generally not included in monitoring programs. However, the total length of small man-made canals in the MD is more than 50,000 km (Truong, 2006), which is a factor 10 higher than the entire length of the Mekong River. Both the hydrological regimes and their use by local population differ from the main waterways with a much more intensive use for various domestic purposes. It cannot *a priori* be assumed that the quality of these secondary canals is similar to that of the main waterways. It is therefore important to assess the water quality and its spatio-temporal variability in these lower order canals and to determine the potentially health-related risks associated with their use. To provide insight into the water quality status and the main sources of pollution in lower order canals, this study addressed the following objectives: 1) analyze the water quality in lower order canals in representative areas and to compare the results with Vietnamese guidelines for drinking and domestic use; 2) compare water quality in lower order canals between inland and coastal regions and water quality attributes from main waterways; 3) identify the factors which explain the spatial variability in surface water quality in lower order canals; 4) assess the effects of tidal regime and seasonality on water quality; 5) spatially visualize water quality of these waterways to identify hot-spot areas of pollution.

4.2 Materials and methods

4.2.1 Study Area

The MD is located in the south of Vietnam. Measurement locations in the MD were selected in three provinces: Can Tho, Hau Giang, and Soc Trang provinces (Fig. 10).

The Mekong River originates in the Tibetian Plateau and flows via China, Myanmar, Lao PDR and Thailand to Cambodia where it enters the Tonle Sap lake. At this location, the Mekong River splits in nine branches (Cuu Long – or nine dragons in Vietnam) and flows through the MD in an easterly direction to the South

China Sea. The climate in this tropical region is influenced by the southwestern monsoon (MRC, 2005). The wet season is generally between May and October with a mean annual rainfall of 1,660 mm (23 years of measurements) (Delta Alliance, 2011). During the wet season, 35% - 50% of the total surface area of the MD is flooded (MRC, 2005). Sea-water intrusion dominates the hydrology along coastal areas with water level fluctuations >3 m per day due to tidal regime. Further inland in the MD, the diurnal tidal movement results in water level fluctuations of 1.0 m to 1.5 m between low and high tide (DONRE, 2011). The MD is well-known for its large density of artificial canals (50,000 km) which are connected to the Mekong distributaries (Truong, 2006). These canals are of three different orders: the primary canals are used for irrigation and water discharge from agricultural fields. They mostly have very low flow velocities roughly between 0 – 1 m^3/s and fall dry during the dry season. The in- and outlet of water in these waterways is often controlled. Secondary canals collect water from surrounding fields and primary canals and discharge into the main (third order) waterways (main canals, rivers). Secondary canals have a water flow around 1 – 15 m^3/s although in coastal regions the water flow is significantly higher (to 30 m^3/s) due to strong influence from the tidal regime. Water flow in main rivers are from a completely different order and roughly between 400 – 6000 m^3/s with the highest flow in the wet season (SIWRR, 2013). Land-use is dominated by intensive agriculture while natural vegetation such as forests occupy less than 10% of the area (MRC, 2005). The dominant land-use system is irrigated rice, representing nearly 50% of the agricultural production. Other agricultural activities include fruit orchards, aquaculture, shrimp farming, livestock rearing and the cultivation of upland crops (maize, sweet potatoes, sugar cane, vegetables) (GSO, 2012b). Various kind and mixtures of fertilizers were used in 2011 – 2012 in the MD in order to maintain and increase agricultural production within particular for rice, fruit orchards and other (upland) crops and include: i) different mixtures of N-P_2O_5-K_2O; ii) Urea (with 46% N); iii) DAP (di-ammonium phosphate; 16-48-0) iv) Lân Super ($Ca_3(H_2PO_4)_2$; 0-20-0) and v) Kaliclorua (0-0-60). Farmers generally have a pattern of mixing two or three of these fertilizers. However, the type and location of agricultural activities is also strongly defined by soil types. Alluvial soils are mainly located near rivers and support diverse field crops; acid sulphate soils are mainly used for rice production; saline soils in coastal areas are mainly used for shrimp farming while on degraded soils and sandy ridge soils along the eastern coastline are used mainly for upland crops and fruit orchards (Guong and Hoa, 2012). Main soil characteristics of the MD are mentioned in Annex 1 (A1.1). Industrial activities have developed rapidly in the region (Nghia, 2001). The total population of the MD was 17.3 million in 2011 (GSO, 2011). Inhabitants in rural areas settle mainly along primary and secondary canals while larger urban settlements are mostly located along the main waterways.

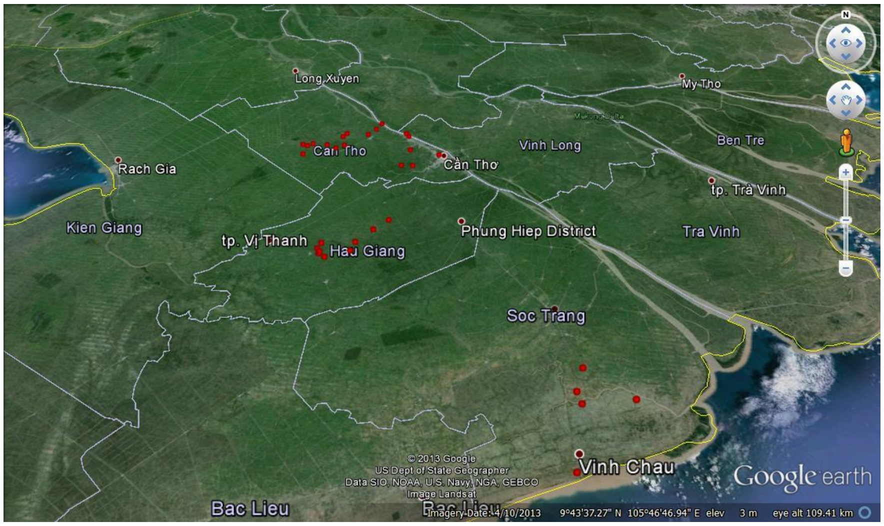


Figure 10 – Map of the central area of the Mekong Delta and the selected water quality monitoring locations (indicated by dots). Monitoring locations were spread in three provinces (Can Tho, Hau Giang and Soc Trang) in order to cover various land-use systems, soil types and distances to main rivers and the coastline.

4.2.2 Sampling locations

Locations for surface water samplings were selected to obtain representative sites for the typical land uses (or in many cases land use mixtures) and soil types of the MD. These were identified using digital maps like satellite images and interviews with local authorities. Sites were subsequently validated *in situ* by investigating the actual land use and to detect potential disturbing factors (e.g. presence of fish farms in orchards dominated area). Sites were located on alluvial-, on slight to moderate acid sulphate- and on saline soils. A total of 32 sampling locations were divided in four areas: i) 18 locations were selected in the Can Tho Province, representative for rice fields, fruit orchards, urbanized/industrial agglomerations, fresh water aquaculture and upland crops. Close to rivers, the soil type was alluvial while in the more inland locations soil types are slightly acid sulphate soils; ii) nine locations were located on moderate acid sulphate soils in Hoa An (Hau Giang Province) representing combinations of rice fields and plots of upland crops such as sugarcane, maize and sweet potatoes and iii) five locations were located on saline soils at Vinh Chau (Soc Trang Province) representing a dense concentration of shrimp farms (Fig. 10). Each of the 27 locations in the Can Tho/Hau Giang Provinces were sampled eight times between November 2011 and July 2012 on a monthly basis, whereas in the five locations in the coastal region of Soc Trang, sampling took place four times on a bi-monthly basis. The sampling period covered both the dry and the wet seasons. All samples were collected during outgoing tide defined by tide tables (DONRE, 2011). Sampling locations were located in secondary canals. Primary canals were not considered due to the small water volume and the low flow velocities that make the water quality of these waterways extremely vulnerable to point source pollution such as the presence of ducks and local fish farming, which could disturb the potential relationship with land-use and/or soil type. Main canals and rivers, on the other hand, were mainly excluded as they contain water from a large variety of areas which complicates the isolation of the effects of land-use and/or soil types on water quality. However, five samples from the Mekong River were collected in order to compare water quality with that of secondary canals.

4.2.3 Analytical procedures

Samples were analyzed for electrical conductivity (EC), total dissolved solids (TDS), pH, turbidity, dissolved oxygen (DO), Chemical oxygen demand (COD), for salts (chloride (Cl^-), sodium (Na)), for nutrients (ammonium (NH_4) nitrate (NO_3), nitrite (NO_2), total-N and ortho-phosphate (o-PO_4), for metal(loid)s (arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), zinc (Zn), aluminum (Al), iron (Fe) and magnesium (Mg)), and for microbial indicators (*E. coli*, other coliform bacteria and total coliforms). PE bottles (100 ml) were used to store water samples for COD, turbidity, TDS, Cl^- and nutrients analysis. For metal(loid) analysis PE bottles (50 ml) were filled with water samples and acidified with 1% nitric acid (65%, Merck Millipore, Billerica, MA, USA). Sterilized 100 ml glass bottles were used to store water for microbial analysis. Sampling occurred from boats or bridges in order to collect water from the centre of canals within the current of the water. The collection of water samples close to canal banks was always prevented since this water was usually standing still and could be of a different quality compared to the middle of the canals (i.e. washing of people close to canals banks). Sampling bottles were held 10 – 30 cm below the surface to prevent intrusion of floating debris in the bottles and the openings of the sampling bottles were held in an opposite direction to that of the water flow. Bottles were closed under water in order to prevent air intrusion. Directly after sampling, the bottles were stored in ice until they reached the laboratory within 8 hours after collection. The EC, DO and pH were measured *in-situ* using a WTW Multi 340i instrument (Weilheim, Germany). For nutrients, Cl^- and COD, all samples were stored at 5 °C, pre-treated by syringe filters (0.45 µm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 hours of collection. The COD, Cl-, NH_4, NO_2, total-N and o-PO_4 concentrations were measured by using Spectroquant ® cell tests (Merck Millipore, Billerica, MA, USA) by applying the following ranges: COD 10 – 150 mg L^{-1}; Cl^- 2.5 – 250 mg L^{-1}; NH_4-N 0.20 – 8.00 mg L^{-1}; NO_2-N 0.002 – 1.00 mg L^{-1}; Total N 0.5 – 15.0 mg L^{-1}; PO_4-P 0.05 – 5.00 mg L^{-1}. NO_3-N was measured using Spectroquant ® cell tests range 0.5 – 18.0 mg L^{-1} although for measurement locations in Soc Trang, seawater proof cell tests were used from

Spectroquant ® cell tests range 0.2 – 17.0 mg L^{-1} (Merck Millipore, Billerica, MA, USA). Unfiltered water was used for turbidity measurements by using a HACH Turbidimeter (Loveland, CO, USA) and TDS and was measured by WTW Profiline Cond 197i (Weilheim, Germany) in unfiltered water. Samples for microbial analysis were treated within 8 hours (EPA, 2002) after sampling under sterile conditions by plating 1 ml of unfiltered sample water on $3M^{TM}$ $petrifilm^{TM}$ coliforms count plates (3M, St. Paul, MN, USA). All samples were diluted twice (10^{-1} and 10^{-2}) with the exception of the samples from urbanized and industrial areas which were diluted three times (10^{-3}). *E. coli* and other coliform colonies were counted 24±4 hours after incubation at 37 ºC. Acidified samples for metal analysis were stored in a fridge at 5°C and analyzed within six months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA).

4.2.4 Data analysis

All statistical analyses were performed using SPSS 20.0 and geographical analyses using ArcGIS 10.

Water quality assessment

Water quality parameters were compared with Vietnamese guidelines established for drinking and domestic uses (Ministry of Health, 2009). The percentages of samples exceeding guideline values were calculated for both the inland areas (Can Tho / Hau Giang provinces) and the coastal region (Soc Trang) to compare water quality between these regions. Moreover, surface water quality in secondary canals was compared with water quality measurements based on the results of five sampling events in main waterways near Can Tho City and regular monitoring data of the MRC and GFZ (MRC, 2007; MRC, 2008; GFZ, 2012).

Spatial differences in water quality were assessed by a Principal Component Analysis (PCA). For this analysis, the initial dataset of 32 sampling locations containing annual median concentrations/levels for all water quality parameters was reduced to fulfill the criteria for the test (Bartlett Test of Sphericity, Kaiser-Meyer-Olkin Measure of Sampling Adequacy (MSA) and determinant). First, all sampling locations at the coastal region were removed due to different hydrological and land-use systems as a result of sea water intrusion. A separate PCA analysis for this region was not performed due to low amount of sampling locations (5). Second, all general parameters, Cl^-, total-N, Mg, *E. coli* and other coliforms caused multicollinearity and were removed. Third, the MSA test was negatively affected by NO_3, As, Cu and Cd due to the low variations in concentrations between the sites and were therefore excluded from the dataset as well. The reduced dataset (COD, Na, NH_4, NO_2, o-PO_4, Al, Ba, Cr, Fe, Hg, Mn, Ni, Zn, total coliforms) was further rotated by varimax with Kaiser Normalization to express the loadings in explaining components.

Temporal variability

The dataset of the 32 sampling sites contains water quality measurements from the dry and wet season in 2011/2012 and was used to assess seasonal differences in water quality at both the inland and coastal regions. The water quality in the dry and wet season was statistically compared with the non-parametric Kruskal-Wallis test since criteria of normal distribution was not met. The differences in water quality between seasons were visualized by box-and-whisker diagrams for ten representative water quality parameters.

The variability of water quality by the tidal regime was investigated by a measurement station located in a tributary of the Hau River near Can Tho City (GFZ, 2012). The distance of this station to the Hau River was less than a hundred meters. Water was measured every fifteen minutes for water level and for EC, TDS, DO and pH levels. The water levels and EC values were plotted graphically from 9 July 2012 to 14 July 2012 to investigate daily fluctuations as a result of the tidal regime.

Water quality maps

Surface water quality maps were developed by linear regression models with land-use and river distance as explaining variables. The water quality parameters O_2, NH_4, o-PO_4, Mn and total coliforms were selected for their strong relationship with either land-use and/or distance to rivers (Annex 1 (A1.2/A1.3)) and represented different groups of water quality parameters as well. The land-use map (Huth *et al.*, 2012) used for regression analysis only covered parts of the Can Tho and Hau Giang provinces and therefore only surface water quality maps of these regions are presented. Median yearly concentrations of twenty sampling locations in Can Tho and Hau Giang were used for regression since these fell within the extent of the land-use map. The concentrations were log-transformed to meet the criteria of the regression analysis (linearity, constant variances, normal distribution, outliers). Only predicting variables (land-use and river distance) that were significantly correlated (Pearson correlation test) with the water quality parameters were used for the linear regression models. Spatial visualization was performed by dividing the entire land-use map of Can Tho / Hau Giang provinces from 2010 (accuracy of 93.7%; ultimate spatial resolution of 10 m (Huth *et al.*, 2012)), in grids of 750-750 m (resulting in 4,144 grid cells). For each grid cell, the percentage of land-use systems and distance to river was defined. The regression models were then used to calculate the concentrations of the selected substances for each grid cell based on this information. The predicted concentrations of each grid cell were interpolated with Inverse Distance Weighting to generate smooth maps. The predicted water quality maps were validated by data from three independent locations. Two measurement locations were purposely excluded for regression analysis to function as validation points. Another validation location was selected from a small scale study area were surface water quality was assessed in a commune close to Can Tho City (Stärz, 2012). The three selected validation locations were geographically spread to cover the entire study area. Validation was carried out by comparing the observed (measured from field data) concentrations with the regression modeled 95% interval confidence range concentrations at the three validation locations. If the observed concentrations from these independent measurement locations fell within the modeled confidence range, the regression model was validated.

4.3 Results and discussion

4.3.1 Differences in water quality between sites and waterways

Table 9 shows all analyzed water quality parameters in secondary canals at inland sampling stations (Can Tho / Hau Giang provinces) and at a coastal region that is influenced by sea water intrusion (Soc Trang province). The median concentrations of five measurements in rivers as well as river water quality data from the Mekong River Commission (MRC, 2007; MRC, 2008) and GFZ (2012) are included to compare water quality between secondary canals and river water.

Dissolved oxygen, COD and turbidity

Table 9 shows that extremely low DO concentrations were observed in waters of the inland regions compared to waters in the coastal areas and in rivers. Significantly higher COD concentrations were detected in lower order canals of the inland region compared to river water. In the waters of the coastal region, high Cl concentrations interfered with COD measurements, so data are not shown. Turbidity levels were highest in lower order canals of the coastal region but drinking and domestic water quality guidelines were exceeded at all investigated sites. High turbidity levels in the coastal region was probably caused by stronger flow velocities in coastal canals due to strong influence of the tidal regime causing fluctuations in water levels of several meters per day. Peak levels of turbidity were also found in urbanized and industrial areas at inland regions most probably caused by untreated waste water effluents. The findings of lower DO and higher COD concentrations in secondary canals of inland regions compared to main rivers suggests that these smaller waterways are more polluted with organic matters. This could be explained by low flow velocities and volumes in combination with intensive use and discharge of waste (visually observed during field visits), leading to the accumulation of organic pollutants. Nevertheless, DO concentrations in secondary canals of the coastal region were higher than those of the inland regions which could be the result of continuous sea water intrusion. DO concentrations in seawater can vary between 3.0 – 9.7 mg L^{-1} as shown in a study near Hong Kong (EPD, 2008). When surface water is used a drinking/domestic water source it is recommended to use river water instead of secondary canal water due to accumulating organic pollutants in these waterways. Moreover, surface water need to be treated intensively in all circumstances to remove organic pollutants and the high levels of turbidity.

Salts

Elevated concentrations of Na and Cl (originating from sea water, sewage water and agricultural soils) increase the electrical conductivity of the water and reduce the suitability for human consumption and irrigation purposes. The highest concentrations of salts (Na and Cl) are found in the secondary canals of the coastal areas exceeding drinking water guidelines for almost all samples. In contrast, guideline values were not exceeded in secondary canals in inland regions and in river water. The constantly high Na and Cl concentrations in the coastal region do not only limit the use of surface water for drinking and domestic purposes but also severely impact rice production. During field visits, it was observed that rice fields in this region are left fallow as cultivation is hampered by saline water intrusion. This finding was also reported by Kotera *et al.* (2008), who detected salt concentrations of up to 35 g L^{-1} in coastal regions of the MD with significant impacts on rice production. The significantly lower salt concentrations in the inland regions suggest that sea water intrusion does not reach the Can Tho / Hau Giang provinces which was also found by a study of White (2002). Nevertheless, salt concentrations in surface waters in secondary canals of the inland regions were higher compared to river water. Secondary canals in the Can Tho / Hau Giang regions receive water from surrounding areas (i.e. rice fields and direct effluents of point sources), locally raising water salinity. Moreover, the exchange rate of these waters is lower leading to accumulations of salts. In general, surface water in coastal regions is too saline for human consumption and irrigation purposes. However, canal water in inland regions and main river water does not exceed guidelines for Cl and Na.

Nutrients

Emissions of (untreated) sewage water and run-off from fertilized agricultural soils are two main sources of nutrients in surface water. In the rural areas, mainly dominated by rice cultivation, the amount of fertilizer use has vastly increased in the last decades from an average of total fertilizer use of 40 kg ha^{-1} in 1976 to over 220 kg ha^{-1} in the period 1995-2003 (Berg, 2002, Lang *et al.*, 2008; Dung, 2007). More recently, interviews with 117 rice farmers conducted in our study in the MD revealed that 105.5 kg ha^{-1} of nitrogen, 73.1 kg ha^{-1} of P_2O_5 and 48.0 kg ha^{-1} of K_2O was used in the wet season of 2011 although fertilizer use in the dry season was lower (81.4 kg ha^{-1} nitrogen; 27.7 kg ha^{-1} P_2O_5; 44.4 kg ha^{-1} K_2O). The large quantities of fertilizers applied by farmers could partially leach out from agricultural fields into the secondary canals. Moreover, primary agricultural field canals do often discharge surplus of water directly to secondary canals. This could explain the observed elevated concentrations of NH_4, total-N and o-PO_4 in secondary canals that were present at almost all locations in the MD. Also potassium (not investigated in this study) is present in elevated concentrations in lower order canals within the range 1.8 – 2.1 mg L^{-1}, as shown by a study of Hoa *et al.* (2006) in Can Tho and Dong Thap Provinces of the MD. However, the exact relationship between fertilizer application on agricultural fields and water quality should be further assessed. In addition, (in)direct sewage effluents from villages and cities may be another cause for elevated concentrations of these nutrients in the water. Nutrient concentrations in water are besides these anthropogenic influences also strongly dependent on several conditions (i.e. temperature, DO concentrations, sun-light penetration) of the receiving water body.

Although relatively high NH_4, o-PO_4 and total-N concentrations were detected in the secondary canals of the inland region this was not observed for NO_2 and NO_3. Instead, the concentrations of these nutrients were low when compared to drinking water guidelines. The low NO_2 and NO_3 concentrations could be caused by the generally low redox potential or DO content, limiting nitrification processes. While, some oxygen was found in the top-layer of the surface water, the concentrations decline rapidly with increasing depths (Johnston *et al.*, 2002). Moreover, available nitrate would be rapidly transformed to N_2O or N_2 due to conditions favoring denitrification. In general, the nutrient concentrations in the coastal region were lower

Table 9

Annual median concentrations/levels, range and guideline exceedance of the surface water quality in secondary canals for physico-chemical parameters, salts, nutrients, metals and microbial indicator bacteria at inland and coastal regions. The median concentrations/values of water quality in main waterways from own observations and other studies are presented to compare with water quality in secondary canals

	VN guidelines[a]		Inland regions (Can Tho / Hau Giang)						Coastal region (Soc Trang)						River water		
	Drinking	Domestic	N	Median	Min	Max	%drink.[b]	%dom.[c]	N	Median	Min	Max	%drink.[b]	%dom.[c]	Own data[1]	MRC[2]	GFZ[3]
Phy.chem. Parameters																	
EC (dS m^{-1})	-	-	223	1.8	0.9	8.2	-	-	25	92.5	5.3	434.0	-	-	1.2	0.2	0.10-0.15
TDS (mg L^{-1})	1,000	-	218	191	101	835	0	-	14	5,098	115	74,600	77	-	132	-	-
pH	6.5-8.5	6.0-8.5	223	6.8	6.2	7.4	11	0	25	7.7	6.9	8.6	0	0	7.5	7.2	7.4-7.7
Turbidity (FTU)	2	5	223	92	18	461	100	100	25	157	44	457	100	100	96	-	10-250
DO (mg L^{-1})	-	-	223	1.7	0.0	5.0	-	-	25	6.0	2.4	7.6	-	-	4.6	6.7	2.0-5.0
COD (mg L^{-1})	-	-	165	22	<10	88	-	-	-	-	-	-	-	-	9	4.8	-
Salts																	
Cl (mg L^{-1})	250	-	94	16	6	130	0	-	15	2,757	110	18,070	64	-	7	9	-
Na (mg L^{-1})	200	-	101	1.5	0.4	7.3	0	-	25	204.8	11.3	761.9	100	-	0.7	2.8	-
Nutrients																	
NH$_4$ (mg L^{-1})	3	3	223	0.8	<0.2	14.7	12	12	25	0.3	<0.2	2.2	0	0	0.2	0.16	-
NO$_3$ (mg L^{-1})	50	-	223	0.6	<0.5	2.9	0	-	25	<0.5	<0.5	0.5	0	-	0.5	0.30	-
NO$_2$ (mg L^{-1})	3	-	223	0.050	<0.002	0.290	0	-	25	0.010	<0.002	0.210	0	-	0.009	-	-
Total N (mg L^{-1})	-	-	72	2.7	<0.5	17.1	-	-	-	-	-	-	-	-	-		
o-PO$_4$ (mg L^{-1})	-	-	223	0.20	<0.05	3.90	-	-	25	0.10	<0.05	0.40	-	-	0.16	0.10	-
Metal(loid)s																	
As (µg L^{-1})	10	10	101	2.4	<2.0	44.1	11	11	25	4.9	<2.0	39.5	14	14	3.1	-	-
Ba (µg L^{-1})	700	-	101	42.2	8.1	157.5	0	-	25	40.3	17.6	82.9	0	-	68.6	-	-
Cd (µg L^{-1})	3	-	101	0.2	<0.1	1.7	0	-	25	0.2	<0.1	0.6	0	-	0.1	-	-
Cr (µg L^{-1})	50	-	101	4.8	<0.4	84.7	1	-	25	8.2	1.9	21.7	0	-	6.1	-	-
Cu (µg L^{-1})	1.000	-	101	3.2	<0.3	36.8	0	-	25	6.0	2.1	39.1	0	-	3.5	-	-
Hg (µg L^{-1})	1	-	101	1.6	<1.2	45.5	67	-	25	1.8	<1.2	13.7	72	-	1.6	-	-
Mn (µg L^{-1})	300	-	101	281.6	59.3	919.4	49	-	25	389.3	26.0	1,659.7	72	-	73.8	-	-
Ni (µg L^{-1})	20	-	101	2.9	0.5	13.3	0	-	25	3.6	<0.4	14.9	0	-	3.1	-	-
Zn (µg L^{-1})	3.000	-	101	10.1	<0.1	108.0	0	-	25	17.0	2.5	44.9	0	-	10.2	-	-
Al (mg L^{-1})	0.2	-	101	1.9	0.2	9.3	99	-	25	3.7	0,1	14.5	96	-	3.2	-	-
Fe (mg L^{-1})	0.3	0.5	101	2.7	0.6	15.7	100	100	25	5.1	<0.3	17.0	96	96	3.6	-	-
Mg (mg L^{-1})	-	-	101	5.6	2.3	11.2	-	-	25	158.6	153.4	417.3	-	-	3.2	5	-
Microbial indicators																	
E. coli (CFU 100 mL^{-1})	0	0	223	3,484	180	87,272	100	100	25	2,713	ND	30,000	80	80	1,432	-	-
Other coli. (CFU 100 mL^{-1})	0	50	223	12,851	2072	2,481,818	100	100	25	5,450	90	34,546	100	100	5,686	-	-
Total coli. (CFU 100 mL^{-1})	0	50	223	16,335	2252	2,569,090	100	100	25	8,163	90	64,546	100	100	7,118	-	-

[a] Vietnamese water quality standards (Ministry of Health, 2009)

[b] Percentage of water samples exceeding the Vietnamese drinking water quality guidelines

[c] Percentage of water samples exceeding the Vietnamese domestic water quality guidelines

[1] Data collected in the Hau River near Can Tho City (n=3 for metals and n=5 for other parameters)

[2] Water quality data extracted from research by the Mekong River Commission (MRC, 2007; MRC, 2008)

[3] Data extracted from continuous water quality measurement station in Hau River near Can Tho City between October 2011 - October 2012 (GFZ, 2012)

N: Number of samples; ND: Not Detected; -:no guideline value set compared to the inland regions. Sea water usually contains lower concentrations of nutrients then fresh water bodies which is confirmed by a variety of studies on coastal water quality such as in Hong Kong and Europe (EPD, 2008; EEA, 2011). Moreover, pollution from point sources is expected to be diluted in the coastal region due to the strong flow velocities in these canals. The lowest NH_4 concentrations were found in main rivers compared to secondary canals. This could be explained by the higher concentrations of dissolved oxygen in rivers which enhances ammonification and nitrification processes in those main waterways.

Although water quality guidelines for nutrients were exceeded for NH_4, observed nutrient concentrations in the MD generally pose little risks associated with drinking and domestic services. Within particular NO_2 and NO_3, who have defined water quality guidelines and may cause methemoglobinemia (Camargo and Alonso, 2006), show low concentrations in water indicating that those health risks are unlikely due to nutrient contamination in the MD.

Metal(loid)s

The presence of metals in surface water can be explained by both natural (i.e. metallic agents that are made available and mobile via reduced conditions) and anthropogenic (i.e. emissions of industrial and/or urban waste water) sources. In the MD, metal(loid) concentrations in secondary canals exceeded drinking water guidelines for As, Cr, Hg, Mn, Al and Fe. Most metal concentrations in coastal regions were higher compared to inland regions. The concentrations of most metal(loid)s in main waterways were similar to those in inland lower order canals except for Ba, Mg and Mn.

The generally low As concentrations in surface water is likely caused by the presence of Fe and Al which reduces the release of As to surface water (Guong and Hoa, 2012). However, the reported peak concentrations with similar concentration levels between 35 - 45 µg L^{-1} were most probably caused by drainage and excavation of canals which leads to oxidation of As-containing sulphide compounds that leach out to the surface water (Guong and Hoa, 2012). Drainage and excavation of canals was observed in many sampled locations during the dry season, due to lower water levels and flow velocities compared to the wet season. This is in line with the observed peaks of As which were detected only during the dry season for short periods of time (< 2 months). This observation is relevant since local people usually collect surface water for drinking during the dry season when other preferred sources like rainwater are not available. The highest Ba concentrations in the MD were found in river water. This could be explained by barite mining activities in riparian countries which results in Ba rich effluents to the Mekong River (Fong-sam *et al.*, 2012). Nevertheless, Ba concentrations did not exceed drinking water guidelines. In contrast, Al and Fe concentrations exceeded drinking water quality guidelines for almost all samples. The presence of these metals is well known in the surface waters of the MD in areas where acid sulphate soils dominate. In these soils, the oxidation of pyrite causes a leaching of these substances to surface waters (Tin and Wilander, 1995). However, Al and Fe concentrations in our study are lower when compared with other studies in the region which showed maximum concentrations of Fe and Al of 182 mg L^{-1} and 104 mg L^{-1}, respectively (Husson *et al.*, 2000; Hoa *et al.*, 2007). Moreover, pH levels in our study were generally observed in the neutral range (6.0 – 8.0) while in typical ASS pH levels drop to < 3.5 (Minh *et al.*, 1997). Hg is another metal that exceeds drinking water guidelines at most location. The presence of this metal is most probably caused by anthropogenic emissions from industrial and urbanized activities. In general, the highest observed metal concentrations were found in secondary canals of the coastal region which may be the result of significantly higher turbidity levels due to stronger flow velocities compared to inland canals. It is well known that metals are strongly bound to suspended solids. Therefore, water with higher turbidity could result in elevated amounts of total metals in comparison with areas that have lower turbidity levels. However, the elevated Mn and Mg concentrations could also be the result of sea water intrusion.

Surface water in the MD was found to exceed drinking water guidelines for a variety of metals especially at secondary canals in the coastal region. The consumption of surface water of secondary canals can therefore lead to severe health-related concerns. This finding is in contradiction with studies to heavy metals concentrations in main rivers of the MD, who concluded that water quality in main rivers with respect to metals was moderate to good and does not cause any level of concern with respect to human health (MRC, 2007). The finding of this study with respect to metal concentrations in secondary canal is relevant since millions of people in the MD rely on this water source for daily purposes.

Microbial indicator bacteria

The number of *E.coli* and other coliform bacteria indicate fecal contamination of the water and are of critical concern with respect to human health. The cell counts of *E. coli* as well as other coliforms were high and exceeded thresholds for drinking water in both regions and in river water. This finding is similar to that reported by Isobe *et al.* (2004) who found *E. coli* cell counts between 10^2 – 10^6 CFU 100 mL^{-1} and total coliforms in the range 10^3 – 10^7 CFU 100 mL^{-1} defined from 22 measurement locations spread over the MD. The high microbial pollution was likely caused by a variety of sources. Firstly, sewage water is rarely treated and is discharged directly to the surface water; a second source could be the presence of animal farms that usually release waste to the environment with no or only primary treatment and a third reason could be ducks that are often raised in canals especially after rice harvesting. A study of microbial pollution in Georgia, USA were sewage water treatments are more common, found *E. coli* concentrations usually in the range $<10^3$ CFU 100 mL^{-1} (Fisher *et al.*, 2000). These concentrations are considerably lower compared with the MD and could confirm the effects of lack of sewage water treatment.

The observed cell counts of microbial indicator bacteria in our study varied between the investigated regions. The highest pollution was observed in the inland region of Can Tho/Hau Giang while in river water pollution was lowest. In Soc Trang province, concentrations are 1.3 – 2.0 times lower compared with the inland region which may be the result of lower population densities, the scarcity of animal farms and strong dilution effects. However, salinity tolerance could also explain the lower observed concentrations of fecal contaminants. The average concentrations of microbial indicator bacteria in main waterways were considerably lower compared to surface waters in the secondary canals. This could be explained by strong dilution of point source emissions by large water volumes and higher flow velocities.

Although, microbial indicators are widely detected in the MD, households usually treat surface water (e.g. boiling and/or chemically) prior to drinking which could decrease the actual health risks associated with consuming surface water. However, this is not the case for other domestic uses such as dish washing, washing vegetables and fruits prior to consumption etc. which might put population at risk.

4.3.2 Spatial variability of water quality

A Principal Component Analysis was performed to investigate which were the main factors explaining the presence of organic pollution (COD), salts, nutrients, heavy metals and microbial pollution in surface water of secondary canals (Fig. 11). Four factors with eigenvalues > 1 were extracted explaining ca. 85% of the total variance of surface water contamination for the selected parameters.

The first component is mainly characterized by Zn, Na and total coliforms. Also NH_4, and o-PO_4 have high loadings compared to other water quality parameters. This component is interpreted as 'urbanization-related pollution'. Coliforms, NH_4 and o-PO_4 concentrations were generally high at measurement locations influenced by villages, cities and industrial areas compared to agricultural rural areas which illustrate the impact of untreated sewage water inputs on surface waters. In addition, Zn had highest concentrations near urbanized areas likely caused by the presence of metal roofs that leach out metals such as Zn during rainfall events. Wilbers *et al.* (2013) found Zn concentrations in harvested rainwater from metal sheet roofs with maximum concentrations of 2.21 mg L^{-1} in the MD. It could explain the higher concentrations of Zn at urbanized locations given the high density of population in villages and cities compared to the rural areas. Na could be explained by emissions of industrial activities as is confirmed by the higher observed salt concentrations (Na: 7.3 mg L^{-1}; Cl: 130 mg L^{-1}) in surface water at a measurement location near an industrial area. The relation between urbanization and elevated concentrations of NH_4, coliforms and metals is also reported by Ren *et al.* (2003) who found a strong positive correlation between urban land use and worsening water quality classifications in Shanghai. Furthermore, a study of the relationship between land-use and water quality in Miami, USA revealed a positive relationship between EC and the percentage of urban land-use (Wang *et al.*, 2007).

The second component comprises of Al, Fe, Cr and Ni and is interpreted as ‘soil leaching’ given the high loadings for the earth metals Al and Fe in the PCA. All the metals in this component were detected in all surface water samples, only the concentrations differed. The effects of metal leaching from soils was also observed by Hoa *et al.* (2007) who found relationships between the presence of metals in surface water (including Al, Fe and Ni) and different acid soil types in the MD. Although severe ASS were not found in our study, this could nevertheless explain the presence of these metals in surface water (see also Annex 1 A1.1).

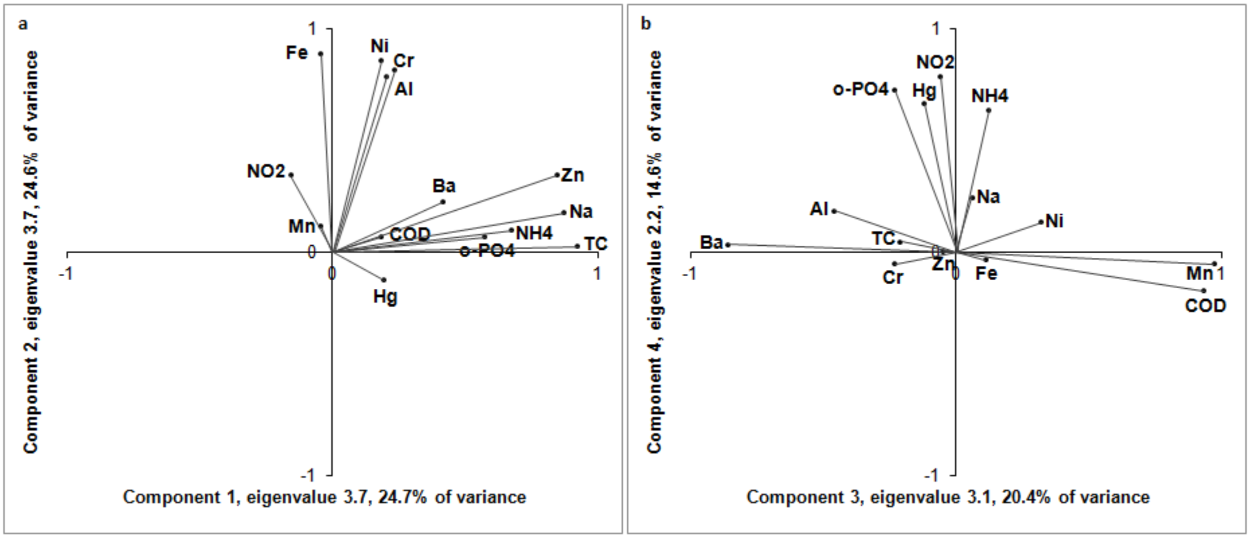


Figure 11 – Loadings of water quality parameters in four principal component (a: component 1 and 2; b: component 3 and 4) with eigenvalues >1.

Note: rotation by varimax with Kaiser Normalization is performed. The dataset contains a reduced amount of water quality parameters in order to meet criteria of the analysis.

TC: total coliforms

The third component comprises of COD, Mn and Ba. This pattern is most probably related to the effects of ‘mixing with fresh water due to the tidal regime’ in the secondary canals. Usually water from secondary canals is refreshed by river water as a result of the tidal movements. However, at locations further away from main rivers these tidal movements may not be sufficient or do not occur at all, leading to a lack of mixing which could result in an accumulation of pollutants such as COD and Mn. Two locations with distances to the Hau River of 0 and 10 km were used to investigate the impact of the tidal regime related to river distance. The water levels of the location close to the Hau River (distance 0 km) differed 1.8 m between low and high tide while the location further away from the Mekong River (distance 10 km) only showed variations of 0.7 m (GFZ, 2012). This confirms the reduced impact of mixing with fresh water with increasing river distance. Moreover, the effects of differences in tidal regime between locations was also observed during field visits when it was visible that canals that lacked tidal movements were more heavily polluted by organic waste compared with canals closer to main rivers. Similar results are also found in the UK, where decreased flow velocities and less mixing of water was shown to lead to higher concentrations of organic pollutants and lower dissolved oxygen concentrations (Whitehead *et al.*, 2009). Although an accumulation of Mn was observed in areas that lacked tidal movements, this pattern was not observed for other earth metals like Al, Cr and Ni. The negative high loading for Ba (-0.86) is in line with the observation that river water contains higher Ba concentrations compared with lower order canals (see also Annex 1 A1.3). This also confirms the influence of the tidal regime on water quality.

The fourth component comprises NH_4, NO_2, o-PO_4 and Hg and is interpreted as the influence of 'aquaculture' on surface water. This is supported by the fact that elevated concentrations of all the mentioned nutrients and Hg were observed at sites near fish farms. The presence of Hg in surface water receiving effluents from fish farms is furthermore confirmed by Choi and Cech (1998) who found unexpectedly high concentrations of Hg in pelleted commercial fish feed. Moreover, a study in Canada detected higher concentrations of Hg in rockfish at locations close to salmon farms (DeBruyn *et al.*, 2006).

4.3.3 Temporal fluctuations of water quality

Tidal movements

Surface water in the MD is influenced by two diurnal tidal movements. This causes fluctuations in water level and impacts water quality due to variations in the dilution of (non)point sources of pollution. Daily variations in water level and quality (EC) due to the tidal regime are shown in Fig. 12 (data: GFZ, 2012).
The highest observed EC levels are visible during outgoing tide (decreasing water levels) which indicates the effects of accumulation of pollutants. Lowest EC levels are observed during incoming tide as a result of fresh river water that has not been severely contaminated yet. Similar results to that of EC are found for concentrations of TDS and DO. However, it was found that pH levels, water temperature and turbidity concentrations did not fluctuate as a result of tidal movements. Nevertheless, the variation of EC levels due to the tidal regime indicates that water quality parameters such as nutrients (NH_4), salts and some metals may show similar patterns. This finding was confirmed by another study on water quality in the MD that found differences in nutrient concentrations between low and high tides (Stärz, 2012). On the other hand, the further inland locations most probably show lower differences in water quality between the tides since tidal fluctuations decrease with increasing river distance from the coastline. Nevertheless, in cases surface water is used for drinking and domestic purposes, it is recommended to collect water during high tide since most pollutants are diluted, a practice generally respected by households in the region.

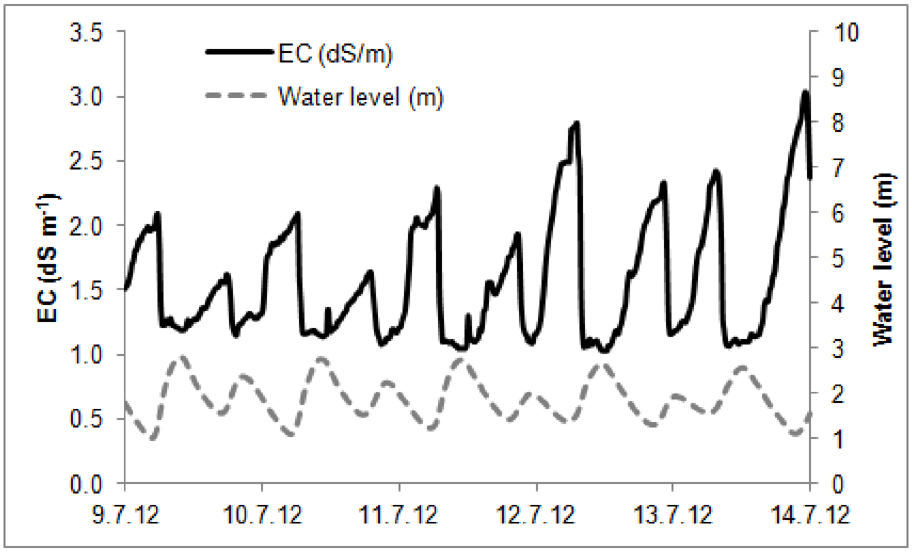


Figure 12 – Variations of EC (black line) and water levels above sea level (dashed grey line) as a result of tidal movements during five consecutive days. The monitoring station was located in a tributary of the Hau River in an area characterized for its intensive urbanized/industrial activities. The distance from the monitoring station to the Hau River was approximately 100 meters. Note the inverse relationship between water- and EC levels.

Seasonality

The monsoonal climate of the MD generates dry and wet seasons. Variations in rainfall events and quantity between seasons affect dilution of (non)point sources of pollution and run-off from both urbanized and agricultural soils.

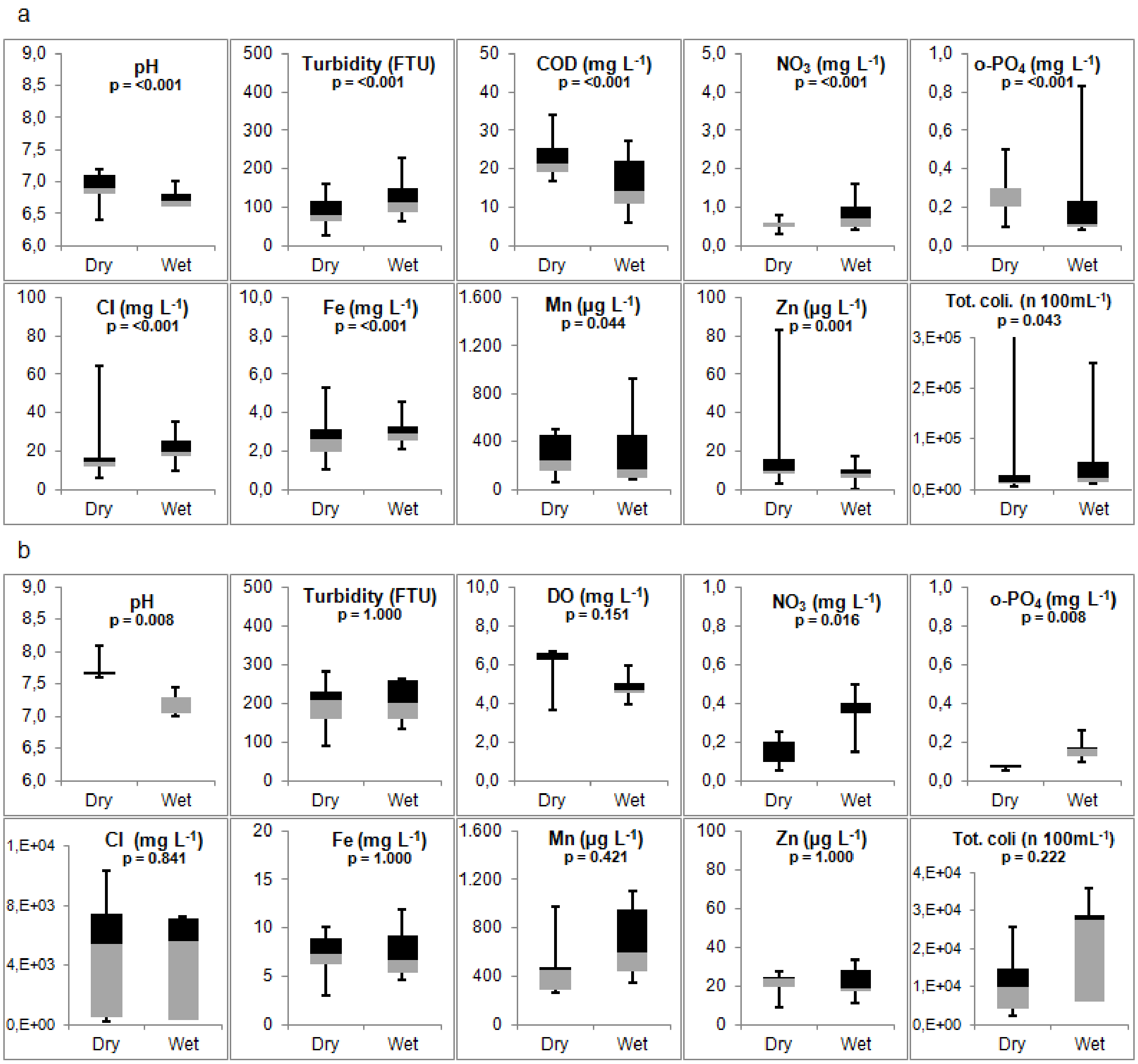


Figure 13 – Differences of selected water quality parameters between seasons visualized by box-and-whisker diagrams for a) the inland locations at Can Tho / Hau Giang provinces (based on 27 locations) and b) the coastal region in Soc Trang Province (based on 5 locations). The boxes represent from bottom to top: minimum, 25th percentile, median, 75th percentile and maximum values derived from the measurements within the selected regions. Note the differences in concentration range (NO_3, Cl, Fe, total coliforms) and significance (p) between the regions. Dissolved oxygen (DO) was selected instead of COD in the coastal region due to high salinity of which interfered with COD measurements.

Fig. 13 shows the seasonal water quality for several representative parameters (pH, turbidity, COD/DO, Cl, NO_3, o-PO_4, Fe, Mn, Zn and total coliforms) at the inland and coastal regions. Fig. 13 shows that there are slightly but statistically significantly lower pH values in the wet season in both regions. This may be the result of higher run-off rates of (acid) soils in the (early) wet season compared with the dry season. Also the higher turbidity and Fe concentrations that were observed in the wet season may confirm this pattern. In the coastal region, however, the differences in turbidity and Fe concentrations between seasons were less pronounced. This could be explained by consistently strong flow velocities compared to the inland regions that cause a continuous erosion of soils regardless of season. The significantly higher Cl concentrations during the wet season at the inland regions could be caused by discharge water from rice fields in the early wet season. During the dry season, salt are accumulated in soil and flushed during the first rainfall events. In contrast, Cl concentrations did not significantly differ between seasons in the coastal region most probably due to continuous sea water intrusion. For nutrients, NO_3 showed highest concentrations during the wet season in both regions while NH_4 concentrations did not vary at all. In contrast, Stärz (2012) found highest concentrations for NO_3 and NH_4 during the dry season in two districts of the MD. The concentrations of o-PO_4 were significantly lower in the wet season for the inland regions although an opposite pattern is visible for the coastal region. These findings suggest that nutrient concentrations vary per location and/or per year. This is especially true for the nutrients, since small changes in the hydrology and/or land-use systems between locations and time can severely disturb the pattern of these substances. The concentrations of Mn were significantly higher during the dry season at the inland region but this pattern was not visible in the coastal region. Similar patterns are visible for the concentrations of COD and Zn. Lower DO concentrations were visible during the dry season in the inland regions (median concentrations: 1.2 mg L^{-1} and 2.2 mg L^{-1} at dry and wet season respectively for inland regions). This could be explained by decreased dilution of waste water effluents during the dry seasons which results in accumulation of pollutants. This finding is in line with the PCA analysis which revealed that Mn and COD accumulate in waterways that lack mixing with fresh water during tidal regime. In the coastal area, this pattern was however not observed most probably due to strong interaction between canal and sea water all year round.

In general, the concentration differences between the wet and dry season were small for most water quality parameters although significant differences between seasons were observed. Furthermore, seasonality does not lead to a shift in guideline exceedence for any water quality parameters. During the dry season, water levels and flow velocities are low which result in an accumulation of pollutants from within particular point sources. In the wet season, these point source emissions are diluted by monsoonal rainfall events. However, such rainfall events increase the run-off from urban and agricultural soils which also contains pollutants. These counteracting mechanisms could explain the relatively small differences in surface water quality between the seasons. This finding is in contradiction with various studies to the effects of seasonality and water quality. Cenci and Martin (2004) for example found that trace metal concentrations in the Mekong River were twice as high in March (dry season) compared to October (wet season). A study in the United States on seasonal effects on water quality found that one water quality parameter can be a significant pollutant in one season and may not be important for another season (Ouyang *et al.*, 2006). Thus, seasonal effects on water quality seem to be small in secondary canals of the MD in comparison with other waterways and regions.

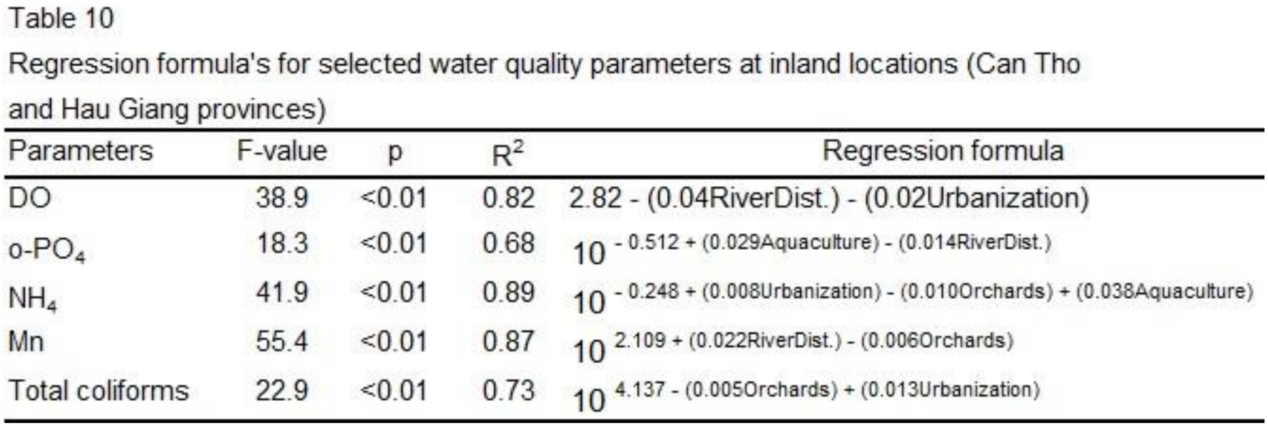


Table 10

Regression formula's for selected water quality parameters at inland locations (Can Tho and Hau Giang provinces)

Parameters	F-value	p	R^2	Regression formula
DO	38.9	<0.01	0.82	2.82 - (0.04RiverDist.) - (0.02Urbanization)
o-PO_4	18.3	<0.01	0.68	$10^{-0.512 + (0.029\text{Aquaculture}) - (0.014\text{RiverDist.})}$
NH_4	41.9	<0.01	0.89	$10^{-0.248 + (0.008\text{Urbanization}) - (0.010\text{Orchards}) + (0.038\text{Aquaculture})}$
Mn	55.4	<0.01	0.87	$10^{2.109 + (0.022\text{RiverDist.}) - (0.006\text{Orchards})}$
Total coliforms	22.9	<0.01	0.73	$10^{4.137 - (0.005\text{Orchards}) + (0.013\text{Urbanization})}$

4.3.4 Hot-spot areas of pollution

Spatial visualization

Surface water quality was found to be related to land-use, mixing of water by the tidal regime (river distance) and soil types (see also Annex 1 (A1.1-A1.3)). Based on these relationships, regression models were developed to predict and visualize surface water quality for one selected general parameter (DO), two nutrients (o-PO_4, NH_4), one metal (Mn) and an indicator for microbial pollution (total coliforms). The selected parameters were chosen for their strong relationship with either land-use and/or river distance.

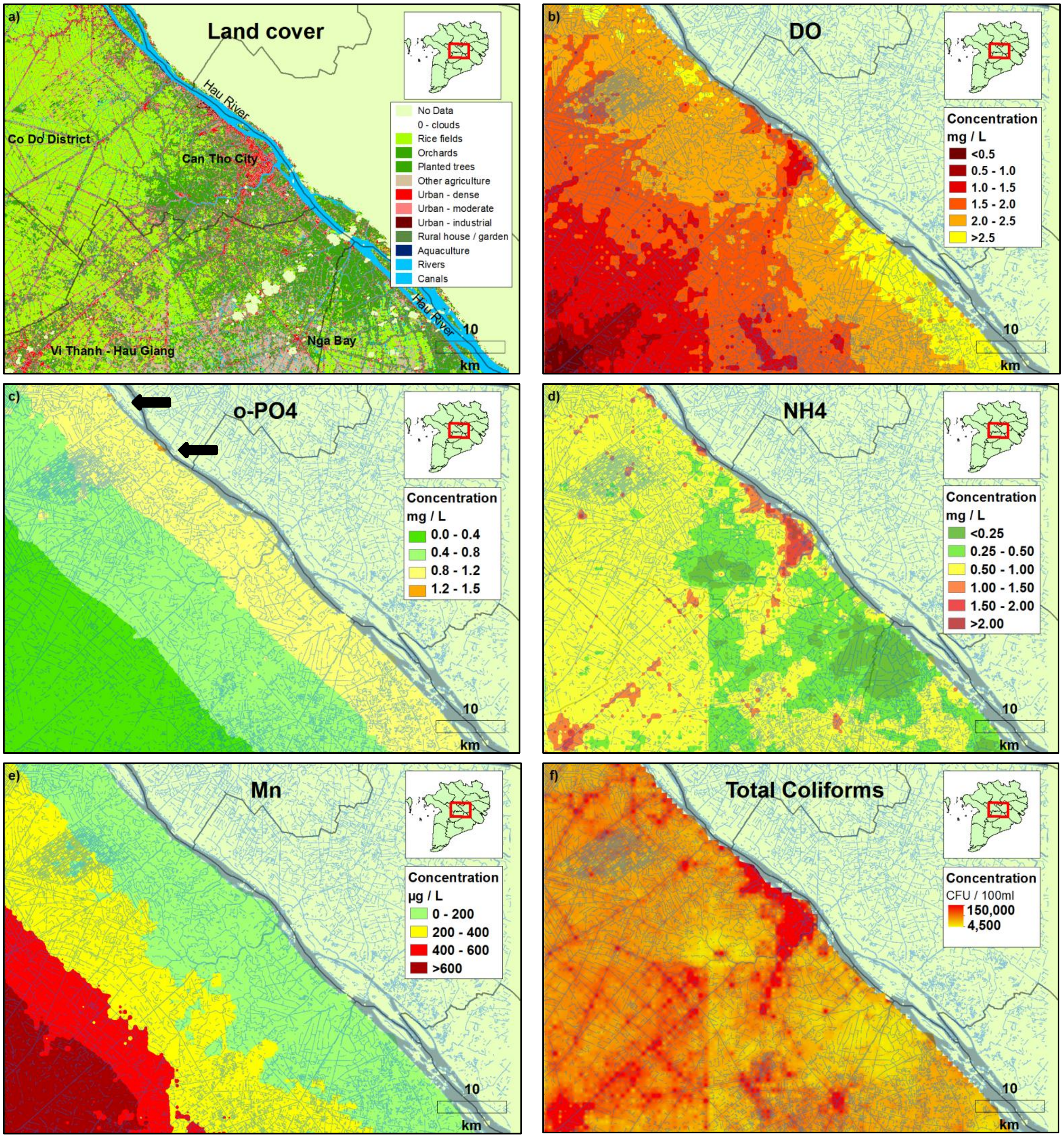


Figure 14 – (a) Land cover map of the inland region of the Mekong Delta (Can Tho and Hau Giang provinces) (Data: Huth *et al.*, 2012); annual median concentrations visualized by regression models based on significant correlations with land-use and or river distance for (b) dissolved oxygen, (c) ortho-phosphate, (d) ammonium, (e) manganese and (f) total coliforms in the secondary canals of the selected region. The blue lines indicate the dense network of artificially constructed secondary waterways and shows what water quality can be expected at a given canal. The blue area in the northwestern part of the maps is caused by the fact that this area is frequently purposely flooded.

Due to different hydrological situation and absence of measurement locations in the northeastern part above the main river, this area was not included for regression and is shown with a light green color. Resolution of maps: 750 meters.

Most other substances with significant correlations with either land-use and/or river distance showed lower R^2 values (< 0.60), which indicates that other factors explain their presence in the surface waters of the MD and were therefore not included in this regression analysis. Earth metals were also not selected for regression since detailed soil maps were not available. Regression modeling was only performed for the inland regions (table 10).

The regression models predict 68% (o-PO_4) to 89% (NH_4) of the variance in the presence of the selected substances in surface water. Aquaculture was the strongest predictor for NH_4 and o-PO_4 whereas distance to rivers had a very strong influence on the concentrations of DO and Mn. Urbanization was the strongest predictor for total coliform concentrations. The regression models of the selected water quality parameters were used to generate surface water quality maps to identify hot-spot areas of pollution (Fig. 14). The maps are based on annual median concentrations of water samples collected during outgoing tide. The water quality maps only represent the secondary canals. Thus, pollutant concentrations in primary- and main waterways may be different from those presented in the maps. Besides land-use and distance to rivers, many other parameters could also impact the water quality such as elevation, differences in precipitation between sites, density of canals and impact of artificial water works like dykes, sluices and dams on the refreshment rate from the tidal regime. However, these parameters were not included in the regression analysis since accurate and/or digital data was not available of these parameters to assess its actual impact on water quality. It is however recommended to further investigate the effects of these parameters on surface water quality as they could be important predictors for water quality as well.

The lowest DO concentrations (Fig. 14a) are visible at the furthest locations from the Hau River. This pattern could be explained by the continuous accumulation of organic pollutants at locations further away from main rivers that reduce the available oxygen in surface water as a result of biological degradation. In some cases, this leads to almost anoxic conditions. However, low DO concentrations are also dependent on the amount of urbanization. An example of low oxygen concentrations is visible within Can Tho City as well as in other urbanized areas. The highest concentrations o-PO_4 are visible next to fish farms near the Hau River (indicated with black arrows) with observed concentrations of 1.5 mg L^{-1} (Fig. 14b). Lowest o-PO_4 concentrations are visible at locations far away from the Hau River. The pattern of lower o-PO_4 concentrations at these locations could be explained by elevated organic pollution at locations further away from the rivers that potentially adsorbs the available o-PO_4 in water. Although at some locations high concentrations of o-PO_4 were observed, algae blooms were not detected in the surface waters of the MD which could be explained by the high turbidity levels that reduce the penetration of sunlight. The lowest NH_4 concentrations (Fig. 14c) are visible in areas that contain high densities of orchards (<0.50 mg L^{-1}). However, the majority of the map shows concentrations above 0.50 mg L^{-1} which are areas generally dominated by rice fields. The observed peaks with concentrations up to >2 mg L^{-1} are visible at urbanized locations like Can Tho City and fish farms which are visible as small orange to red dots on the map. This finding is particularly relevant for water supply companies since NH_4 concentrations >0.50 mg L^{-1} could severely affect the disinfection efficiency by chemical treatment such as chlorination (EU, 1998). The concentrations of Mn (Fig. 14d) are strongly related to the distance to main rivers with concentration of concerns in these areas. These high concentrations are in line with PCA analysis which also indicated the accumulation of this metal in surface water where mixing with fresh water is reduced. The concentrations of total coliforms (Fig. 14e) are, similar to that of NH_4, being lowest in orchard dominated areas although drinking water guideline values are exceeded at all locations. Nevertheless, large differences are visible in total coliform concentrations with the highest observed values within urbanized areas as well as along main infrastructures such as main roads that also contain high densities of houses.

These findings are especially relevant to policy makers to detect hot-spot areas of pollution and to develop water management strategies. The presented maps could also be of interest for water supply and ice-producing companies to define treatment systems and optimal locations for water extraction. The presented surface water quality maps are especially designed for such practitioners since those maps are easier to understand compared to correlation tables and regression formula’s. Moreover, the presented techniques of the development of surface water quality maps could also be used for other regions world-wide to inform a broad audience besides scientists.

Validation

Data from 20 measurement locations were used to develop regression models and surface water quality maps. In order to assess the accuracy of water quality predictions in other areas, the modeled concentrations were validated with observed concentrations at three independent locations. Validation points were selected at locations that represented various land-use systems and different distances to main rivers (Table 11).

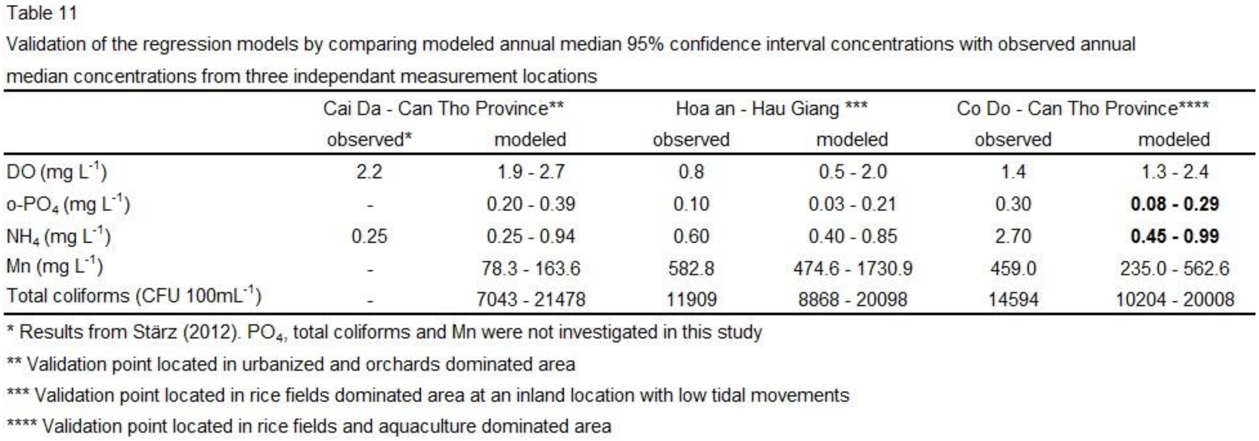


Table 11

Validation of the regression models by comparing modeled annual median 95% confidence interval concentrations with observed annual median concentrations from three independant measurement locations

	Cai Da - Can Tho Province**		Hoa an - Hau Giang ***		Co Do - Can Tho Province****	
	observed*	modeled	observed	modeled	observed	modeled
DO (mg L^{-1})	2.2	1.9 - 2.7	0.8	0.5 - 2.0	1.4	1.3 - 2.4
o-PO_4 (mg L^{-1})	-	0.20 - 0.39	0.10	0.03 - 0.21	0.30	**0.08 - 0.29**
NH_4 (mg L^{-1})	0.25	0.25 - 0.94	0.60	0.40 - 0.85	2.70	**0.45 - 0.99**
Mn (mg L^{-1})	-	78.3 - 163.6	582.8	474.6 - 1730.9	459.0	235.0 - 562.6
Total coliforms (CFU 100mL^{-1})	-	7043 - 21478	11909	8868 - 20098	14594	10204 - 20008

* Results from Stärz (2012). PO_4, total coliforms and Mn were not investigated in this study

** Validation point located in urbanized and orchards dominated area

*** Validation point located in rice fields dominated area at an inland location with low tidal movements

**** Validation point located in rice fields and aquaculture dominated area

Location Cai Da, representing the land use mix "urbanization/orchards", showed that DO and NH_4 concentrations were predicted within the validation range although observed concentrations were close to the lower modeled boundary. This validation data point (Stärz, 2012) was collected in 2008 which could have slightly different climatologic and or land-use conditions in comparison with our measurements in 2011/2012. The observed measurements in Hoa An, representing rice fields and a river distance of >30 km, fitted well with the modeled values. The validation location Co Do, representing rice fields and aquaculture, showed two observed measurement concentrations above the modeled values (NH_4 and o-PO_4). This finding highlights the uncertainty of modeling surface water quality around small but heavily polluting point sources such as (fish) farms due to large variation in the hydrology of canals as well as variability in the emissions. In summary, the regression models generally predict surface water quality within the validation range (95% confidence interval) except occasionally, for local point sources such as fish farms. These water quality maps should be used as a first screening to get an indication of the likelihood of pollution at specific locations. However, recent water quality measurements are required when the actual water quality is needed at a specific location due to strong variation in local hydrology and the potentially strong influences of point sources.

4.4 Conclusions

Secondary canals are intensively used by local populations for both drinking and domestic services. The quality of these waters is generally poor, especially compared to main water systems such as rivers. Thus the usage of this water can lead to severe health concerns, particularly near point sources (fish farms) and within industrial/urbanized agglomerations. Most water quality monitoring campaigns in the MD focus on main canals and rivers. Due to the intensive use and pollution of secondary canals it is therefore recommended to set-up water management strategies to monitor and improve the local water quality for different regions and time intervals. Furthermore, educational programmes should be organized to inform local populations about risks of using surface water and effective water treatments to improve its quality.

Household should also be encouraged to use surface water only during incoming tide since the quality is better compared to outgoing tides. However, people that live within a close distance to main sources of pollution (fish farms, industrial areas, large villages, cities) should be discouraged to use surface water from secondary canals at all and alternative water supply facilities should be put in place by local authorities. Based on the water quality maps, hot-spot areas of pollution can be identified which is also relevant for drinking water companies to define ideal water extraction locations. Based on the results of this study, landscapes with predominantly fruit orchards seem to be promising locations since most investigated pollutant concentrations were low in these areas, although screening for pesticides from these systems should also be considered.

5. Spatial visualization of groundwater quality contamination in the lower Mekong Delta

Abstract

Many studies on groundwater quality in Southeast Asia refer to elevated concentrations of arsenic and other trace metals leading to health related risks. However, detailed studies on groundwater quality and its spatial variation are scarce to date, despite the fact that groundwater is a main drinking water source for the population. In order to fill this information gap and using the Mekong Delta in Vietnam as a representative location in Southeast Asia we collected a total of 116 groundwater samples at household pumps following a predefined grid sampling method in an inland (Can Tho/Hau Giang provinces) and in a coastal (Soc Trang Province) region between July and September 2012. Water samples were analyzed for general parameters (EC, pH, turbidity), Cl, TOC, nutrients (NH_4, NO_3, NO_2, o-PO_4, total-N, SO_4), metals (As, Ba, Cd, Cr, Cu, Hg, Mn, Ni, Zn, Fe, Mg) and microbial indicator bacteria (*E. coli*, total coliforms) and compared with WHO drinking water guidelines. Causes for groundwater contamination were assessed. Hot-spot areas of pollution were spatially visualized by using Gaussian Geostatistical Simulation in ArcGIS. The results show that drinking water guidelines are exceeded for many parameters including Cl (max. 2860 mg L^{-1}), NH_4 (max. 29.0 mg L^{-1}), As (max. 30.2 µg L^{-1}), Ba (max. 1597.6 µg L^{-1}), Mn (max. 4016.2 µg L^{-1}) and *E. coli* (max. 600 CFU $100mL^{-1}$). Causes of pollution are both from anthropogenic (e.g. extensive groundwater extraction leads to saline intrusion) and natural (i.e. dissolution of As-rich iron phases under reductive conditions) origin. Spatial hot-spot maps of pollution were developed for Cl, NH_4, As and Mn which shows large variability between sites. Significant areas are affected by salinity intrusion, making groundwater unsuitable for any purpose. The highest concentrations of NH_4 were found in the coastal region affecting disinfection efficiency. As and Mn hot-spot areas were also detected, indicating health-related risks zones. Spatial risk maps as presented in this study are unique for the MD and the approach could prove useful for other regions in the MD and other countries. The results of this study can be used by decision makers and drinking water companies to refine water management strategies by defining locations where groundwater is (not) suitable for drinking and/or define required treatment measures in order to reduce health-related concerns associated with the consumption of polluted groundwater.

5.1 Introduction

Groundwater in river basins of South and Southeast Asia are well-known to be severely contaminated with arsenic (As) affecting tens of millions of people in the densely populated river deltas (Winkel *et al.*, 2008; Fendorf *et al.*, 2010). Most of these studies focus on the severe arsenic pollution in groundwater in Bangladesh. The concentration of arsenic in this country is ca. 50 – 2500 µg L^{-1} and is causing severe health concerns such as skin lesions, gangrene in legs, as well as skin, lung, bladder, liver and renal cancers (Anawar *et al.*, 2002). The quality of groundwater in the Mekong catchment area and in the Red River delta is also intensively investigated with respect to As contamination. In the Red River Delta, groundwater was found to exceed international drinking water guidelines for As ($\geq$ 10 µg L^{-1}) with average concentrations between 39 – 348 µg L^{-1} (Berg *et al.*, 2007; Nguyen *et al.*, 2009). This is in line with Postma *et al.* (2007) who also reported As in groundwater in the Red River delta and found that the source of As was related to the decomposition of organic compounds. Groundwater near the Mekong River in Lao PDR, in the Mekong Delta of Cambodia and in the western part of the Vietnamese Mekong Delta have also been investigated in detail and were found to be contaminated with As and other trace elements such as barium (Ba), manganese (Mn) and iron (Fe) (Berg *et al.*, 2007; Shinkai *et al.*, 2007; Buschmann *et al.*, 2008; Hoang *et al.*, 2010; Chanpiwat *et al.*, 2011). Erban *et al.* (2013) found that clay compaction in deep aquifers (200 – 500 meters below surface area) due to extensive groundwater extraction may lead to As release and/or to the release of As mobilizing solutes resulting in deep groundwater not being a long-term safe water source for populations. Lado *et al.* (2008) spatially visualized As concentrations in the shallow groundwater in

Cambodia and found hot-spot areas of pollution although the maps show large uncertainties regarding observed concentrations. Other contaminants in groundwater in South and Southeast Asia were also found to cause severe (health-related) risks. A study on groundwater quality in Bangladesh, for example, found *E. coli* in 12% and 43% of groundwater samples from deep and shallow wells respectively (Leber *et al.*, 2011). Groundwater with high salinity is another potential and increasing concern for drinking water provision in coastal areas. Nuber *et al.* (2005) found chloride concentrations in Can Tho and Hau Giang provinces of the MD ranging between 150 and 1,200 mg L^{-1} which indicates that water is not suitable for drinking due to its saline taste.

Despite the relatively large amount of groundwater studies in South and Southeast Asia and considerable groundwater extraction for drinking purposes, the groundwater quality in large areas of the Vietnamese MD is not investigated in detail yet. On the other hand, groundwater has become an increasingly important water source since the mid-1990s for many rural households in the MD (Berg *et al.*, 2006). Other major drinking water sources like harvested rainwater are namely not available all year round (Wilbers *et al.*, 2013), while surface water is highly contaminated with microbial pollutants (Isobe *et al.*, 2004; Wilbers *et al.*, in preparation) and pesticides (Sebesvari *et al.*, 2012; Toan *et al.*, 2013) and affected by saline intrusion especially in the coastal areas (Tuong *et al.*, 2003), which makes this source unsuitable for drinking without proper treatment. Piped water from supply stations on the other hand is still too expensive and perceived as unreliable for most rural households (Reis and Mollinga, 2009; Wilbers *et al.*, in preparation). Given the increasing reliance on groundwater, which may also be caused by socio-economical development of the MD (Garschagen *et al.*, 2012) and its documented pollution in similar regions, it is important to develop risk-maps that show where groundwater may be potable.

Various studies have attempted to spatially visualize groundwater quality to identify hot-spot areas of pollution in Southeast Asia (Buschmann *et al.*, 2008; Lado *et al.*, 2008; Winkel *et al.*, 2008). Although hot-spot areas of pollution could be identified, all studies had to cope with large uncertainties due to strong spatial variability in groundwater quality. However, simulation techniques could decrease the uncertainty of groundwater modeling since it includes this variability (Deutsch and Journel, 1998). Such simulation techniques to visualize hot-spot areas of pollution for groundwater bodies in the MD have not been applied although this could provide suitable information for decision makers in the region.

The objectives of this study were therefore: i) to investigate the groundwater quality at an inland and a coastal region in the Vietnamese MD, for nutrients, salts, heavy metals and microbial indicator bacteria and compare results with international drinking water guidelines and with data from other studies in the Mekong River basin; ii) to assess the sources and/or conditions that cause pollution in groundwater bodies for the selected regions; iii) assess the influence of well depths on groundwater quality and iv) identify and visualize hot-spot areas of pollution by simulation techniques that includes local variability that more accurately show locations were groundwater is (not) safe for drinking and were potentially extraction locations for water supply stations could be placed.

5.2 Materials and methods

5.2.1 Study area

Sampling locations were selected at two inland provinces (Can Tho / Hau Giang) and one coastal province (Soc Trang) of the MD (Fig. 15).

The MD is located in the south of Vietnam and belongs to the Mekong basin which originates in the Tibetian Plateau and flows via China, Myanmar, Lao PDR, Thailand and Cambodia before reaching Vietnam. In the MD, the river (known as the *Cuu Long* in Vietnam) splits in nine branches and flows to the South China Sea (referred to as the East Sea in Vietnam). The elevation levels are 0.5 – 1.2 m above sea level except for areas along the Cambodian border that has slightly higher elevations (Tri, 2012). The total population of the MD was 17.4 million in 2012 (GSO, 2012a). Settlements are widely spread in the MD, since most people prefer to live along the banks of natural or man-made canals. The soils are rich in minerals and organic compounds and are therefore intensively used for various agricultural activities including rice, orchards and other upland crops (GSO, 2012b). The MD was formed by sediments from the Mekong River from upstream countries. The deposition and accumulation of these sediments over millions of years has resulted in the formation of several aquifers and aquitards with a total maximum thickness of 600 m (Anderson, 1978). This formation can generally be divided in five hydro geological units (Wagner *et al.*, 2012): i) the Holocene aquifer has a maximum depth of 30 meters and extends over the entire MD. The water quality in this aquifer is generally poor with high salinity, high levels of pollutants and in some areas extremely low pH values due to leaching from acid sulphate soils (IUCN, 2011); the use of water from this aquifer for drinking purposes is therefore limited; ii) the upper-middle Pleistocene aquifer is roughly located between depths of 30 – 150 meters throughout the MD. The water in these aquifers is reported to be generally of good quality with low salt concentrations (Wagner *et al.*, 2012). Therefore, these groundwater sources are intensively used for domestic water supplies in the MD; iii) the lower Pleistocene aquifer can be found to depths of maximum 250 meters. In the southeastern areas of the MD, the lower Pleistocene has direct contact with the upper-middle Pleistocene aquifer. The water is generally reported to be of good quality as well and is exploited by water supply stations in Can Tho, Kien Giang, Bac Lieu and Ca Mau provinces (Wagner *et al.*, 2012); iv) the middle-lower Pliocene aquifers can roughly be found between depths of 200 – 400 meters and also contains water that is reported of generally good quality. Water supply stations in Dong Thap, Long An, Can Tho, Bac Lieu and Ca Mau exploit this aquifer for drinking water supplies; v) the upper-middle Miocene aquifers can be found at depths >350 meters. Water from these aquifers is not intensively used although water quality may be of high quality (Wagner *et al.*, 2012). The households that were selected for this study sourced groundwater from wells with depths between 30 – 130 m below surface (interview result), which corresponds to the upper-middle Pleistocene aquifer.

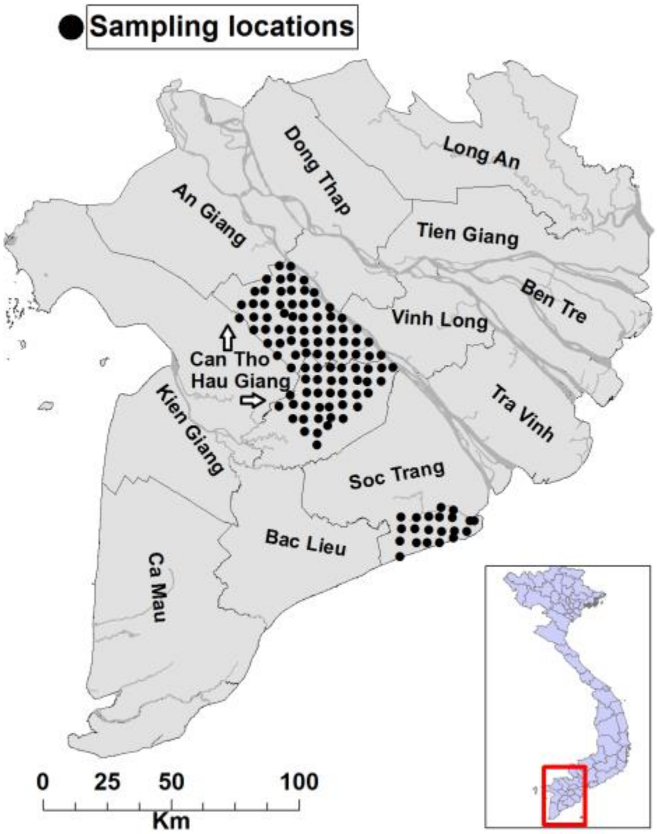


Figure 15 – Groundwater sampling locations in the inland (Can Tho / Hau Giang provinces) and the coastal region (Soc Trang province)

5.2.2 Sampling and analytical procedures

All groundwater samples were collected between 22 July and 23 September 2012 which corresponds to the rainy season in the MD. A total of 116 household groundwater wells (95 in the inland region and 21 in the coastal region) were selected on a regular five kilometer interval grid to avoid clusters of measurement locations (Fig. 15). The locations were defined desk-based and localized by GPS in the field (Garmin ETrex, Olathe, KS, USA). The household closest to the pre-defined location using groundwater was selected for sampling. Selected households were also interviewed to collect information about well depth and personal perception of water quality. Prior to sampling, wells were purged for 10 minutes. Samples were collected directly from the well. However, some wells were equipped with plastic tubes in order for people to use groundwater for different purposes (e.g. watering the garden, cleaning the house, add water to storage basin for drinking). PE bottles (250 mL) were used to store water samples for turbidity, pH, Cl and nutrients analysis. Fifty ml PE bottles were filled with water samples and acidified with 1% nitric acid (Merck Millipore, Billerica, MA, USA) for (heavy) metal analysis. Fifty mL glass bottles were used to store water samples for TOC analysis while sterilized hundred mL glass bottles were used to store water for microbial analysis. After sampling the bottles were stored on ice until they reached the laboratory within 12 hours after collection. Each location was sampled only once.

Samples were analyzed in the laboratory for electrical conductivity (EC), chloride (Cl), pH, turbidity, total organic carbon (TOC), for nutrients ammonium (NH_4), Nitrate (NO_3), Nitrite (NO_2), ortho-phosphate (o-PO_4), Total-N and sulphate (SO_4), for metal(loid)s including total arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), zinc (Zn), iron (Fe) and magnesium (Mg) and for microbial indicators (*E. coli* and total coliforms). Unfiltered water was used for turbidity measurements by using a HACH Turbidimeter (Loveland, CO, USA) and EC and pH were measured by WTW Multi 340i instrument (Weilheim, Germany) in the laboratory. For nutrients and Cl, all samples were stored at 5 °C, pre-treated by syringe filters (0.45 µm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 hours of collection. The NO_3, NO_2, o-PO_4, NH_4, Total-N, SO_4 and Cl concentrations were measured by using Spectroquant® cell tests (Merck Millipore, Billerica, MA, USA) by applying the following ranges: NO_3-N: 0.5 – 18.0 mg L^{-1}; NO_2-N: 0.002 – 1.00 mg L^{-1}; PO_4-P: 0.05 – 5.00 mg L^{-1}; NH_4-N: 0.20 – 8.00 mg L^{-1} and 0.5 – 16.0 mg L^{-1}; Total N: 0.5 – 15.0 mg L^{-1}; SO_4: 50 – 500 mg L^{-1}; Cl: 2.5 – 250 mg L^{-1}. For samples with Cl concentrations > 250 mg L^{-1}, NO_3-N was measured by seawater proof cell tests of Spectroquant® cell tests range 0.2 – 17.0 mg L^{-1} while Total N was not analyzed for those samples. The other nutrient tests were not negatively affected by high Cl levels. Prior to SO_4 analysis, the colorimetric sulphate test with test strips MQuant™ was applied to define the measurement range. Unfiltered water was used for TOC measurements by applying Low Range Test 'N tube™ (HACH, Loveland, CO, USA) with measurement range of 0.3 – 20.0 mg L^{-1}. Samples with Cl > 500 mg L^{-1} were excluded for TOC analysis. Acidified samples for metal analysis were stored in a fridge at 5°C and analyzed within six months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA). Samples for microbial analysis were treated within 8 hours after sampling under sterile conditions by plating 1 mL of sample water on 3M™ petrifilm™ coliforms count plates (3M, St. Paul, MN, USA) in duplicates. *E. coli* and other coliform colonies were counted 24±4 hours after incubation at 37 ºC.

5.2.3 Data analysis

Statistical tests were performed with SPSS 20.0 and geographical analyses with ArcGIS 10. The correlations between water quality parameters with explaining variables and well depth were demonstrated by the non-parametric Spearman´s rho test since most of the data were not normally distributed, even after log-transformation (tested by Shapiro-Wilk-test).

A scoping study of groundwater quality in three small areas in the Can Tho / Hau Giang provinces undertaken in the frame of this work showed that even at small distances, groundwater quality fluctuates considerably (see annex 2 on local variability of groundwater quality). Thus, simple interpolation techniques like kriging were not suitable to develop accurate groundwater quality maps to identify hot-spot areas of pollution. Therefore, spatial groundwater quality maps were developed by Gaussian Geostatistical Simulation (GGS) which considers the variability of datasets (Deutsch and Journel, 1998). For GGS, first interpolation maps using simple kriging techniques for the selected water quality parameters by selecting semivariogram modeling were developed. Simple kriging was performed with normal score transformation since datasets were not normally distributed. Declustering and first order of trend removal were also required for GGS. All other options were left as standard. The output of the simple kriging model was then conditioned in GGS with the initial groundwater quality dataset to better identify hot-spot areas of pollution. A total of 100 realizations were defined. At each point in the landscape, the model builds up a distribution probability of potential pollutant concentrations based on the actually measured concentrations. The output of these simulations are presented via groundwater quality maps for selected parameters for the calculated 0.1 and 0.9 quantile concentrations which represent a ‘good case’ and a ‘bad case’ scenario, respectively. Hot-spot areas of pollution were defined for areas that exceed WHO drinking water guidelines for both the 0.1 and 0.9 quantile maps. Potential hot-spot areas are defined in areas that exceed WHO drinking water guidelines for the 0.9 quantile maps but not for the 0.1 quantile maps. Non hot-spot areas of pollution are defined as region where no guidelines were exceeded at the 0.9 quantile maps.

5.3 Results

5.3.1 Water quality

Table 12 summarizes the analytical results for 116 groundwater samples and compares the results with internationally defined drinking water guidelines set by the WHO and the EU for both the inland and coastal regions.

The selected groundwater samples exceeded secondary drinking water guidelines for Cl in 24% to 29% of the samples in the inland and coastal regions, respectively. Water with Cl concentrations above 250 mg L^{-1} has a saline taste and is therefore inappropriate for drinking. Most of the pH values in groundwater were in the neutral range (6.5 – 8.5), although some groundwater samples showed slightly acid conditions with a minimum observed pH value of 5.0 in the inland region. Turbidity levels also exceeded secondary drinking water guidelines. Among nutrients, NO_2 and NO_3 concentrations were low and did not exceed drinking water guidelines in any of the samples. However, the concentrations of NH_4 and SO_4 exceeded secondary drinking water guidelines for a majority of the samples. The highest concentrations of these nutrients were found in the coastal region with maximum concentrations of 29.0 mg L^{-1} and >1000 mg L^{-1} for NH_4 and SO_4 respectively. Ortho-phosphate was present in almost all samples above the detection limit (0.05 mg L^{-1}), but this substance does not have defined guideline levels with respect to human health. Among metals, mainly Fe and Mn concentrations exceeded guideline values, followed by As and Ba. In general, the lowest metal concentrations were observed in the coastal region. Over one-third of the samples were tested positively for *E. coli* and/or total coliforms in both inland and coastal regions.

5.3.2 Correlation between water quality parameters

The above described water quality parameters are partially correlated with each other. Correlation coefficients of water quality parameters exceeding drinking water guidelines with all investigated water quality parameters are presented in table 13.

Measured pH values were negatively correlated with As and Fe concentrations in the inland region while this pattern was not observed in the coastal areas. In the inland region, TOC was positively correlated with pH while the correlation was negative for the coastal region. For both inland and coastal regions, significant correlations are visible between EC, Cl, Mg. High correlation coefficients were found between NH_4 and total-N concentrations (0.92 and 0.99 for inland and coastal regions respectively) which indicate that nitrogen components in groundwater mostly occur as NH_4. Other significant relationships between water quality parameters and NH_4 were not found in the coastal area although multiple parameters showed significant relationships with NH_4 at the inland regions.

SO_4 showed an inverse significant relationship with Ba concentrations. No significant relationship was found between SO_4 and As concentrations. Instead, As was strongly correlated with Fe and turbidity at both sites. In the coastal areas, As and Cl concentrations were positively correlated while an opposite pattern was visible in the inland region. Arsenic was furthermore significantly related to pH values and NO_2, NO_3 and o-PO_4 concentrations in the inland region.

E.coli and total coliform counts in groundwater were not related with any of the investigated water quality parameters.

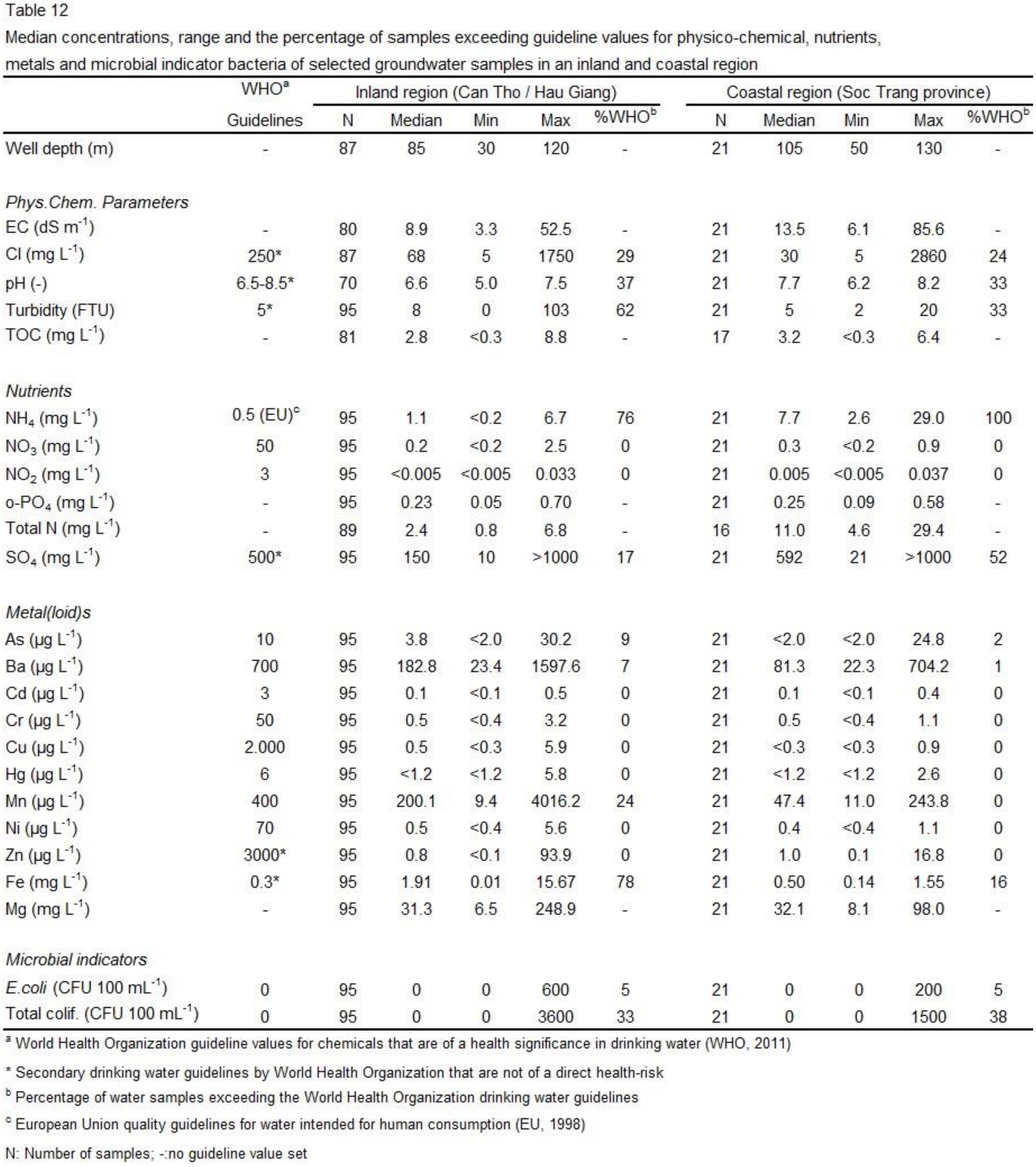


Table 12

Median concentrations, range and the percentage of samples exceeding guideline values for physico-chemical, nutrients, metals and microbial indicator bacteria of selected groundwater samples in an inland and coastal region

	WHO[a] Guidelines	Inland region (Can Tho / Hau Giang) N	Median	Min	Max	%WHO[b]	Coastal region (Soc Trang province) N	Median	Min	Max	%WHO[b]
Well depth (m)	-	87	85	30	120	-	21	105	50	130	-
Phys.Chem. Parameters											
EC (dS m^{-1})	-	80	8.9	3.3	52.5	-	21	13.5	6.1	85.6	-
Cl (mg L^{-1})	250*	87	68	5	1750	29	21	30	5	2860	24
pH (-)	6.5-8.5*	70	6.6	5.0	7.5	37	21	7.7	6.2	8.2	33
Turbidity (FTU)	5*	95	8	0	103	62	21	5	2	20	33
TOC (mg L^{-1})	-	81	2.8	<0.3	8.8	-	17	3.2	<0.3	6.4	-
Nutrients											
NH_4 (mg L^{-1})	0.5 (EU)[c]	95	1.1	<0.2	6.7	76	21	7.7	2.6	29.0	100
NO_3 (mg L^{-1})	50	95	0.2	<0.2	2.5	0	21	0.3	<0.2	0.9	0
NO_2 (mg L^{-1})	3	95	<0.005	<0.005	0.033	0	21	0.005	<0.005	0.037	0
o-PO_4 (mg L^{-1})	-	95	0.23	0.05	0.70	-	21	0.25	0.09	0.58	-
Total N (mg L^{-1})	-	89	2.4	0.8	6.8	-	16	11.0	4.6	29.4	-
SO_4 (mg L^{-1})	500*	95	150	10	>1000	17	21	592	21	>1000	52
Metal(loid)s											
As (µg L^{-1})	10	95	3.8	<2.0	30.2	9	21	<2.0	<2.0	24.8	2
Ba (µg L^{-1})	700	95	182.8	23.4	1597.6	7	21	81.3	22.3	704.2	1
Cd (µg L^{-1})	3	95	0.1	<0.1	0.5	0	21	0.1	<0.1	0.4	0
Cr (µg L^{-1})	50	95	0.5	<0.4	3.2	0	21	0.5	<0.4	1.1	0
Cu (µg L^{-1})	2.000	95	0.5	<0.3	5.9	0	21	<0.3	<0.3	0.9	0
Hg (µg L^{-1})	6	95	<1.2	<1.2	5.8	0	21	<1.2	<1.2	2.6	0
Mn (µg L^{-1})	400	95	200.1	9.4	4016.2	24	21	47.4	11.0	243.8	0
Ni (µg L^{-1})	70	95	0.5	<0.4	5.6	0	21	0.4	<0.4	1.1	0
Zn (µg L^{-1})	3000*	95	0.8	<0.1	93.9	0	21	1.0	0.1	16.8	0
Fe (mg L^{-1})	0.3*	95	1.91	0.01	15.67	78	21	0.50	0.14	1.55	16
Mg (mg L^{-1})	-	95	31.3	6.5	248.9	-	21	32.1	8.1	98.0	-
Microbial indicators											
E.coli (CFU 100 mL^{-1})	0	95	0	0	600	5	21	0	0	200	5
Total colif. (CFU 100 mL^{-1})	0	95	0	0	3600	33	21	0	0	1500	38

[a] World Health Organization guideline values for chemicals that are of a health significance in drinking water (WHO, 2011)

* Secondary drinking water guidelines by World Health Organization that are not of a direct health-risk

[b] Percentage of water samples exceeding the World Health Organization drinking water guidelines

[c] European Union quality guidelines for water intended for human consumption (EU, 1998)

N: Number of samples; -:no guideline value set

Table 13

Spearman's rho correlation coefficients between selected water quality parameters exceeding drinking water guidelines and all measured water quality parameters for the inland and coastal regions

	Inland region (Can Tho / Hau Giang provinces)										Coastal region (Soc Trang Province)									
Parameters	pH	Turbidity	Cl	NH_4	SO_4	As	Ba	Fe	Mn	Tot. Coli	pH	Turbidity	Cl	NH_4	SO_4	As	Ba	Fe	Mn	Tot. Coli
pH	---	-.25	.14	.08	-.02	**-.48***	-.09	**.45***	.08	.20	---	.53	**.62***	.23	.18	.35	.15	.32	.38	-.24
Turbidity	-.25	---	-.13	**.43***	.13	**.41***	-.06	**.64***	**-.42***	-.13	.53	**---**	**.70***	-.13	.13	**.69***	.02	**.87***	.47	-.36
EC	.12	.06	**.69***	**.46***	**.45***	-.24	.22	-.12	.14	.18	.31	**.59***	**.81***	.20	.13	**.74***	.20	.50	.54	-.00
Cl	.14	-.13	---	-.07	-.21	**-.38***	**.43***	-.08	**.45***	.27	**.62***	**.70***	---	.04	-.18	**.59***	.43	**.59***	.54	-.31
NH_4	.08	**.43***	-.07	---	**.53***	.15	**-.41***	.05	**-.39***	.01	.23	-.13	.04	---	.26	.14	.06	-.28	-.02	.14
NO_3	-.23	.05	-.21	.09	**.28***	**.31***	-.12	.23	.05	.04	-.49	-.49	-.52	.33	-.18	-.21	-.04	-.34	.41	.35
NO_2	**-.37***	**.29***	-.27	.23	.17	**.28***	-.07	.20	-.19	-.15	.14	.30	.01	-.38	-.10	.21	.04	.26	.17	.05
o-PO_4	-.23	.11	**-.44***	-.07	-.09	**.33***	-.02	**.33***	-.09	-.06	.03	-.03	.22	.09	**.55***	.05	**.72***	.10	.12	.15
SO_4	-.02	.13	-.21	**.53***	---	.08	**-.69***	.13	.04	.05	.18	.13	-.18	.26	---	.22	**-.66***	-.01	.29	.07
TOC	**.41***	**.29***	.17	**.38***	.07	.15	-.07	.04	-.12	.10	**-.82***	-.60	**-.64***	-.04	-.28	-.19	.17	-.36	-.14	.49
Total N	.03	**.44***	-.13	**.92***	**.48***	.16	**-.39***	.01	**-.41***	-.02	.23	.31	.49	**.99***	.48	.51	-.10	-.02	.44	-.07
As	**-.48***	**.41***	**-.38***	.15	.08	---	-.13	**.43***	-.24	-.07	.35	**.69***	**.59***	.06	.22	---	.16	**.70***	.53	.04
Ba	-.09	-.06	**.43***	**-.41***	**-.69***	-.13	---	.10	.24	-.07	.15	.02	.43	-.05	**-.66***	.16	---	.15	.11	.01
Cd	-.28	**.27***	.21	-.10	.06	.12	.13	**.53***	.23	.09	.29	.29	.29	.21	.23	**.61***	-.03	.37	.34	.25
Cr	.01	.06	**.41***	.25	.18	-.10	.01	.12	.20	.02	.33	.49	.47	.21	.13	.30	.04	.50	.28	-.05
Cu	-.02	**.27***	-.06	.08	.14	.18	.10	.24	.05	.05	.07	-.10	.03	.21	-.40	-.14	.45	-.05	-.38	.14
Fe	**-.45***	**.64***	-.08	.05	.13	**.43***	.10	---	.00	-.06	.32	**.87***	**.59***	-.28	-.01	**.70***	.15	---	.44	-.20
Hg	-.06	.06	.07	.00	-.02	-.08	-.03	.04	.05	-.15	-.17	-.20	-.18	-.25	-.29	-.34	-.13	-.21	-.41	.10
Mg	.22	-.04	**.62***	**.30***	**.43***	-.21	-.05	.03	**.31***	.13	.40	**.58***	**.77***	.11	.12	-.21	.27	**.59***	**.60***	-.06
Mn	.08	**-.42***	**.45***	**-.39***	.04	-.24	.24	.00	---	.08	.38	.47	.54	.02	.29	-.53	.11	.44	---	-.08
Ni	-.22	-.04	-.06	**-.28***	-.22	.02	.06	-.01	.09	-.17	-.22	-.19	-.06	-.25	-.39	-.21	.05	-.19	-.50	-.05
Zn	-.22	.08	.24	-.22	-.07	.10	**.27***	**.30***	**.28***	.18	**-.59***	**-.75***	-.52	-.04	-.11	.42	.12	-.55	-.44	.51
E. coli	.10	-.05	.21	-.06	.04	-.15	.00	-.02	.19	**.40***	-.08	.21	.33	.00	-.30	.22	.37	.22	-.11	-.17
Total Colif.	.19	-.13	.27	.00	.05	-.07	-.07	-.06	.08	---	-.24	-.36	-.31	.14	.07	.04	.01	-.20	-.08	---

* Significant correlation at $p \leq 0.01$

5.3.3 Effects of well depth on water quality

Although groundwater samples were all collected within the upper-middle Pleistocene aquifer, groundwater quality was found to be correlated with well depth for some of the monitored parameters (Fig. 16). Turbidity levels and concentrations of total-N and As are positively correlated to well depth indicating that generally higher levels/concentrations were found in deeper wells. An opposite pattern was observed for concentrations of Cl and Mn which showed highest concentrations at shallow wells. Although these correlations are significant, the relationship between well depth and these water quality parameters can be regarded as weak due to low R-values (<0.5). All other water quality parameters not shown in Fig 16, were not significantly correlated to well depth for the Can Tho / Hau Giang region. No significant correlations were found between any water quality parameter and well depth in the coastal region.

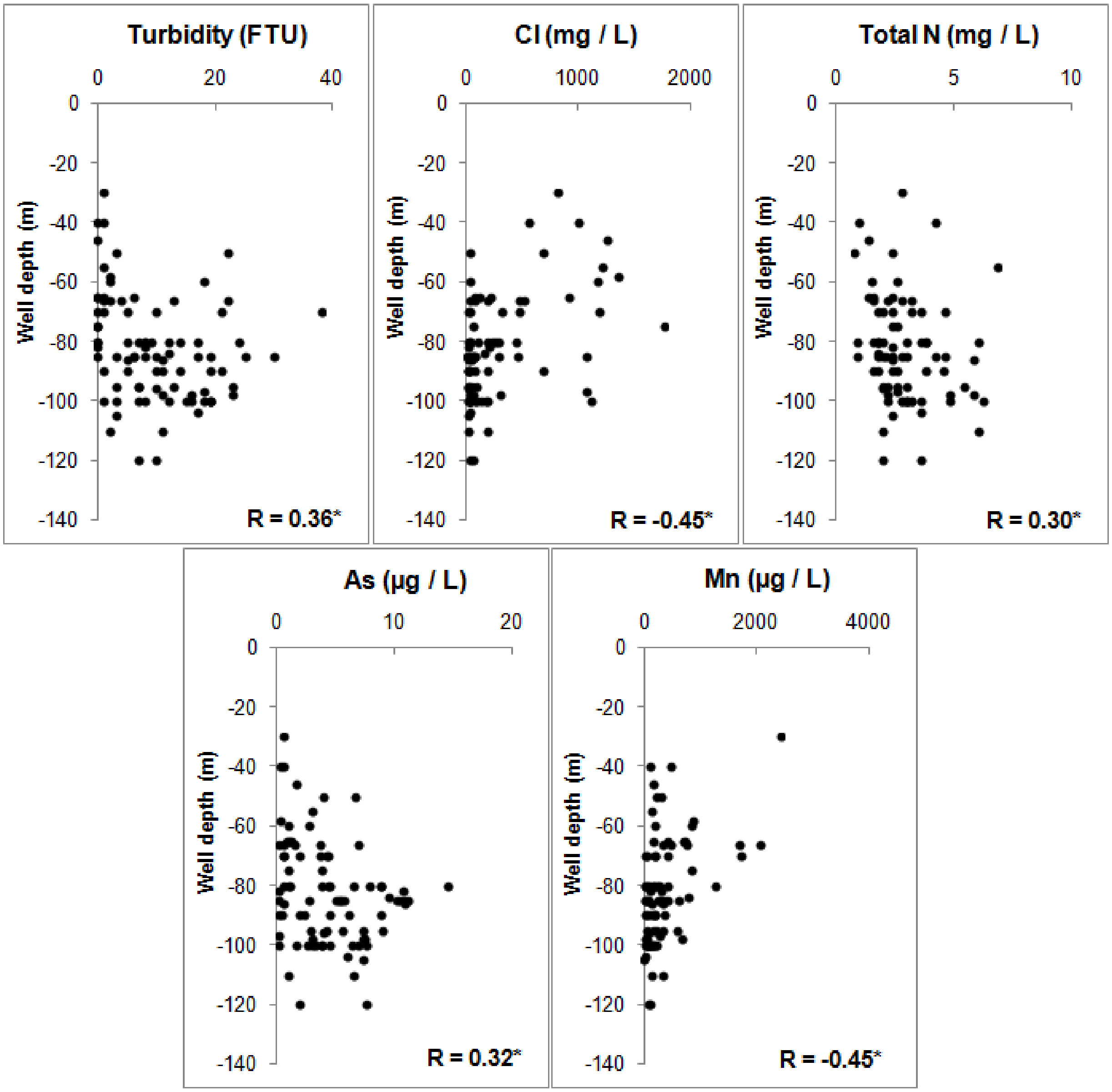


Figure 16 – Relationship between well depth with levels of turbidity and concentrations of Cl, Total-N, As and Mn for groundwater in Can Tho / Hau Giang provinces. The statistical correlation coefficient (R), defined by the Spearman´s rho test, is provided for every parameter.

* significant correlation at the 0.05 level

5.3.4 Groundwater quality maps

Groundwater quality maps were developed for salinity (Cl), a nutrient (NH_4) and two metals (As and Mn) to identify hot-spot areas of pollution (Fig. 17). These parameters were selected based on the fact that they frequently exceeded guideline values (Table 12). In addition, As was selected for its well-known severe health concerns. Hot-spot areas of elevated Cl concentrations (Fig. $17a_1$) in groundwater bodies are localized in the southern area of the inland region (Hau Giang province) and in the northern area of the coastal region. For example, in the Hau Giang Province predicted Cl concentrations are roughly between 800 – 900 mg L^{-1} and 1200 – 1500 mg L^{-1} for the 0.1 and 0.9 quantile outputs respectively. Thus, there are predicted concentration differences between the different quantile values. Since both quantiles predict concentrations above 250 mg L-1 (drinking water guideline), a redbrown color is visible for both 0.1 and 0.9 quantile maps. Therefore, this area is identified as a hot-spot area for Cl contamination.Potential hot-spot areas of elevated Cl concentrations are predicted to occur near Can Tho City, Co Do district and even at some locations close to the Hau River. However, the maps also show that in many locations groundwater does not have elevated Cl concentrations, even in the coastal region (Fig. $17a_2$). NH_4 concentrations of concern are predicted in almost all investigated sites although areas with lower NH_4 concentrations are also found in the western part of the inland region. Nevertheless, guidelines could also be exceeded at those locations given the concentrations above 0.5 mg L^{-1} for the 0.9 quantile map (Fig. $17b_2$). No obvious hot-spot areas of pollution are identified for As, as simulated concentrations are below 10 µg L^{-1} for the As 0.1 quantile map (Fig. $17c_1$). However, based on the As 0.9 quantile map (Fig. $17c_2$), several potential hot-spot areas in the inland region can be identified. Large differences in simulated Mn concentrations are visible between the 0.1 and 0.9 quantile maps for the inland region (Fig. $17d_{1,2}$). Therefore, obvious hot-spot areas of Mn pollution cannot be identified. However, the maps show that Mn can be potentially found almost everywhere in the inland region at concentrations exceeding drinking water standards. In comparison, Mn concentrations in the coastal region are low and do not show any (potential) hot-spot area of pollution.

5.4 Discussion

5.4.1 Comparison between locations in the lower Mekong basin

Groundwater quality in the MD was found to exceed multiple drinking water guidelines. Nevertheless, large differences in groundwater quality can be observed within various areas of the lower Mekong River basin (Table 14). The comparison of groundwater quality between sites should however be used only as an indications of potential differences between locations due to differences in investigated well depths and measurement times and procedures. As expected, salt concentrations (Cl and Mg) in groundwater are generally higher in the downstream regions which could suggest the influence of sea water intrusion in coastal areas. However, Cl concentrations in Soc Trang were lower compared to Can Tho / Hau Giang provinces. This could be the result of intensive irrigation in Can Tho/Hau Giang provinces which enhances salt water intrusion. Thus, high saline groundwater could be found in regions further located from the sea as well. Nutrient concentrations are more difficult to compare between locations, since most studies do not investigate groundwater quality for those parameters. However, one study in Cambodia showed that NO_3 and NH_4 concentrations are similar to those in our study sites although SO_4 concentrations were significantly lower in Cambodian groundwater compared with the Soc Trang, Can Tho/Hau Giang provinces (Buschmann *et al.*, 2008). Higher median As concentrations were monitored in upstream regions of the lower Mekong River basin. Ba and Mn concentrations on the other hand, show large variability between sites. Lower Fe concentrations are visible at upstream locations of the Mekong River basin (Cambodia, Lao PDR). Despite differences in median concentrations between regions for As, Ba, Mn and Fe, all studies reported on groundwater samples that exceeded drinking water guidelines for these metals (Hoang *et al.*, 2010; Buschmann *et al.*, 2008; Chanpiwat *et al.*, 2011). These findings suggest that groundwater can be contaminated at almost every location in the lower Mekong River basin. This finding is in line with Winkel *et al.* (2008) who concluded that As is widely spread in groundwater in Southeast Asia.

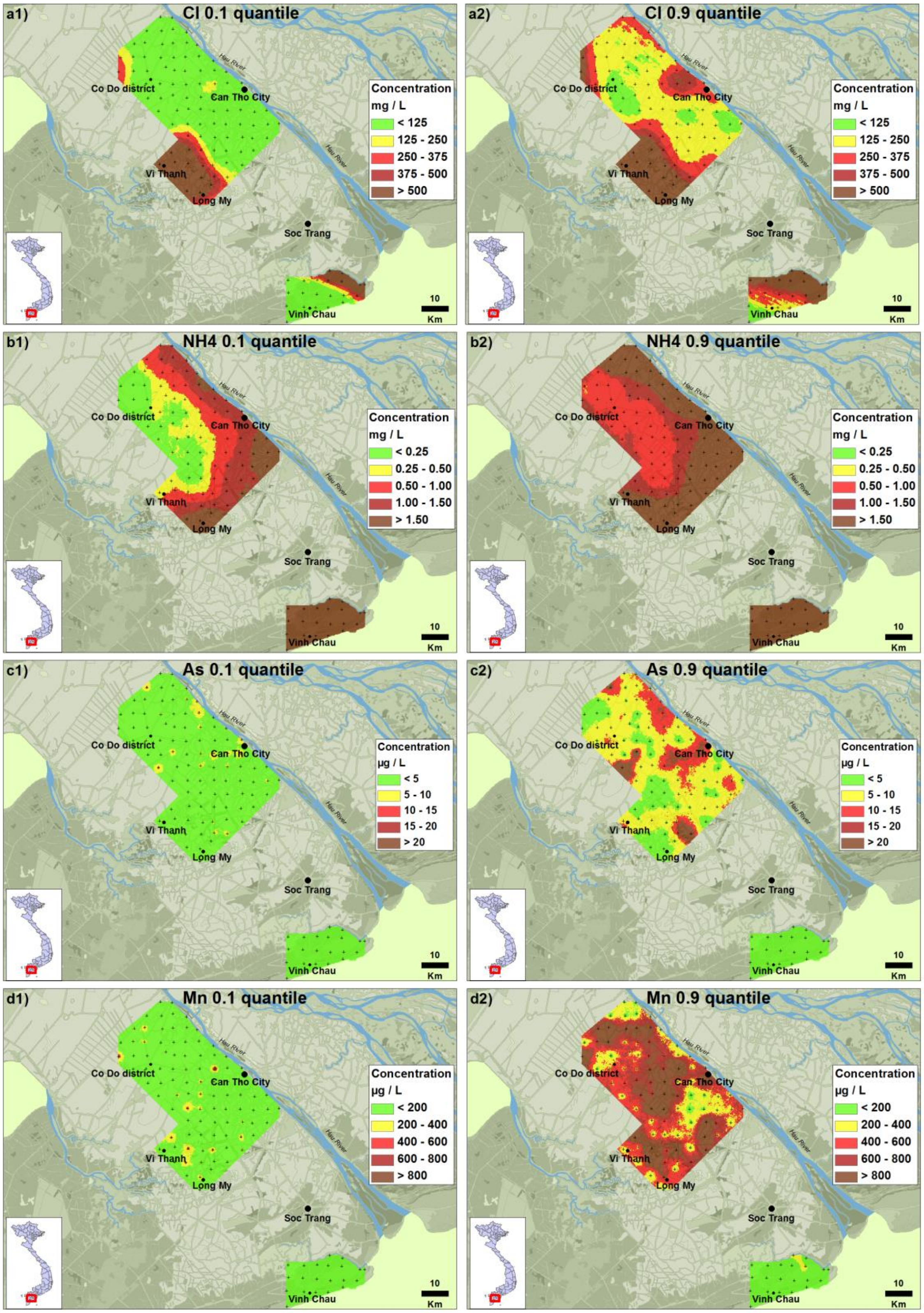


Figure 17 – Simulated groundwater quality maps for 0.1 and 0.9 quantile concentrations to identify (potential) hot-spot areas of pollution for Cl, NH_4, As and Mn using Gaussian Geostatistical Simulation. Potential hot-spot areas of pollution are distinguished when guidelines are exceeded (red-brown colors) for the 0.9 quantile maps but not for the 0.1 quantile maps. Hot-spot areas of pollution are identified when guideline exceedings are observed in both 0.1 and 0.9 quantile maps.

Differences in median concentrations for other investigated metals like Cu, Ni and Zn are also visible between regions in the lower Mekong River basin although these metals are of a lower concern with respect to human health given the fact that concentrations are below drinking water guidelines set by the World Health Organisation (WHO, 2011). Differences in metal concentrations observed between studies (Table 14) could be explained by: i) spatial variations in psychical-chemical processes in groundwater bodies between regions; ii) variations in investigated well depths and analytical procedures between studies and iii) differences in land-use between regions that could also severely impact groundwater quality.

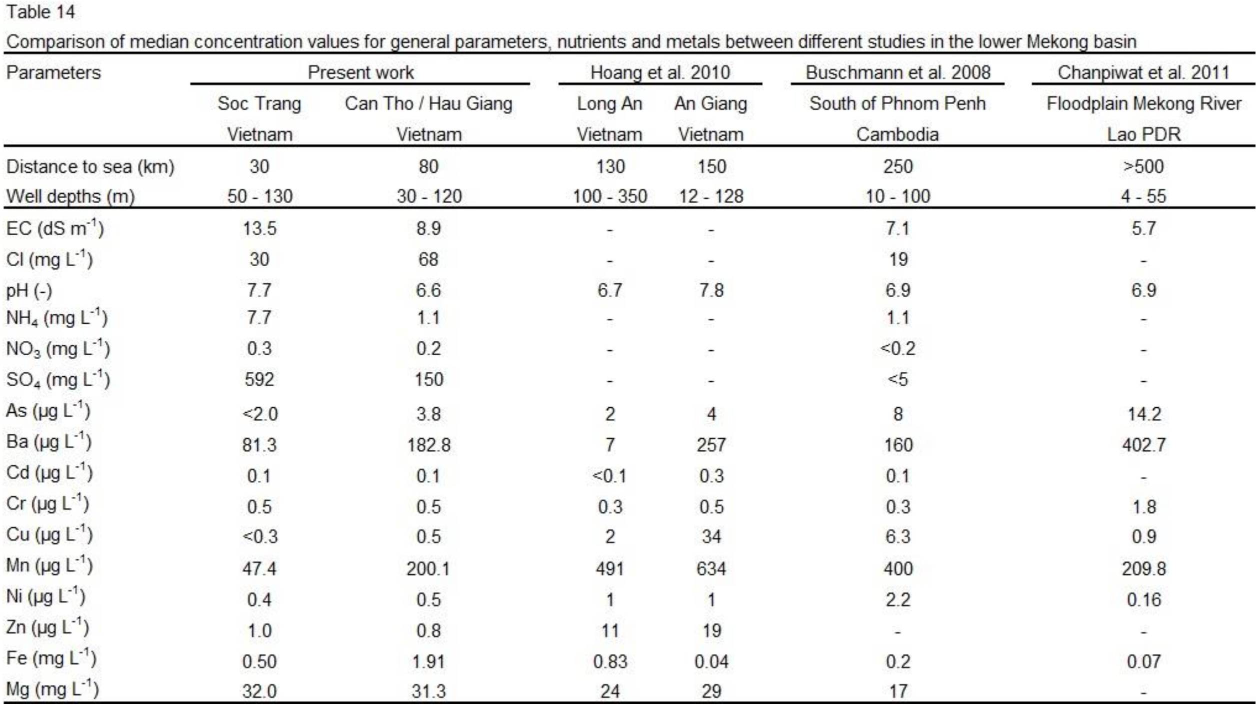


Table 14

Comparison of median concentration values for general parameters, nutrients and metals between different studies in the lower Mekong basin

Parameters	Present work		Hoang et al. 2010		Buschmann et al. 2008	Chanpiwat et al. 2011
	Soc Trang Vietnam	Can Tho / Hau Giang Vietnam	Long An Vietnam	An Giang Vietnam	South of Phnom Penh Cambodia	Floodplain Mekong River Lao PDR
Distance to sea (km)	30	80	130	150	250	>500
Well depths (m)	50 - 130	30 - 120	100 - 350	12 - 128	10 - 100	4 - 55
EC (dS m^{-1})	13.5	8.9	-	-	7.1	5.7
Cl (mg L^{-1})	30	68	-	-	19	-
pH (-)	7.7	6.6	6.7	7.8	6.9	6.9
NH_4 (mg L^{-1})	7.7	1.1	-	-	1.1	-
NO_3 (mg L^{-1})	0.3	0.2	-	-	<0.2	-
SO_4 (mg L^{-1})	592	150	-	-	<5	-
As (µg L^{-1})	<2.0	3.8	2	4	8	14.2
Ba (µg L^{-1})	81.3	182.8	7	257	160	402.7
Cd (µg L^{-1})	0.1	0.1	<0.1	0.3	0.1	-
Cr (µg L^{-1})	0.5	0.5	0.3	0.5	0.3	1.8
Cu (µg L^{-1})	<0.3	0.5	2	34	6.3	0.9
Mn (µg L^{-1})	47.4	200.1	491	634	400	209.8
Ni (µg L^{-1})	0.4	0.5	1	1	2.2	0.16
Zn (µg L^{-1})	1.0	0.8	11	19	-	-
Fe (mg L^{-1})	0.50	1.91	0.83	0.04	0.2	0.07
Mg (mg L^{-1})	32.0	31.3	24	29	17	-

5.4.2 Causes of pollution in the MD

Salinity

Although saline groundwater hot-spot areas have been identified in this study, most samples showed Cl concentrations below drinking water guidelines, even in the coastal areas. Possible reasons for the relatively low Cl and Mg concentrations of groundwater in the coastal area could be explained by: i) a continuous recharge of groundwater bodies via rainwater infiltration by coastal sand ridges forming fresh water lenses, ii) a submarine fresh groundwater aquifer or iii) an ancient fossil fresh water storage. Groundwater that is replenished by rainwater via sandy coastal ridges would most probably contain higher concentrations of NO_2 and NO_3 due to generally higher oxygen concentrations in sandy ridges. However, groundwater in the coastal region is strongly reduced and does not contain high concentrations of these nutrients. Instead, almost all available nitrogen is present as NH_4 which is confirmed by the strong correlation between total-N and NH_4 concentrations. Moreover, infiltrated rainwater in groundwater bodies would most likely also contain more organic pollutants (TOC) and pathogens that are largely present in top-soils in the Mekong Delta as a result of intensive agricultural activities and human settlements. However, both TOC and pathogen concentrations are similar to those in the central provinces. In various coastal areas in the world, submarine groundwater sources were shown to originate from fresh groundwater aquifers (Knee and Paytan, 2011). Thus, groundwater bodies near coastal areas and even under the sea may contain water with low salinity. The presence of a submarine fresh water aquifer could explain why some groundwater wells with a distance of only few hundred meters from the coastline contained low Cl and Mg concentrations. Groundwater with low salt concentrations in the coastal region may also originate from a fossil source, separated from its surrounding environment. However, more investigation is required in the MD with respect to the occurrence of low saline groundwater in the coastal region. This is especially important since fresh groundwater is intensively used for irrigation and drinking water supply in coastal areas since surface water sources are too saline.

A main hot-spot area of saline groundwater has been identified in the south of the inland region (Fig. 17a$_1$). This hot-spot area could be due to over-exploitation of groundwater sources which results in a drop of groundwater levels that leads to increased salt water intrusion from either coastal areas or other more saline aquifers. This finding is supported by Reis and Mollinga (2009) who found that groundwater levels are dropping at a rate of 0.5 – 0.7 m/year in the Can Tho and Hau Giang provinces caused by groundwater extraction. This finding is also confirmed by household interviews that were conducted in rural communities in the south of the inland region (Hau Giang province) and where many people indicated that groundwater was not salty and good for drinking until a few years ago and was used extensively by the households. This finding is relevant since groundwater in other, non affected regions, could also become saline due to over-exploitation, which is especially critical in coastal regions where alternatives such as surface water are not suitable for drinking or irrigation due to sea water intrusion (Wilbers *et al.*, 2014).

In summary, it is important to manage the use of fresh groundwater supplies in the MD especially in regions that depend on this source for drinking in order to serve future generations. Moreover, desalinization techniques such as reverse osmosis may still be too complex and expensive for rural developing regions like the MD (Nuber *et al.*, 2005). It is therefore recommended to: i) use groundwater from wells >100 meters that most likely contains lower Cl concentrations (Fig. 16); ii) to use alternative sources for irrigation like surface water instead of the valuable fresh groundwater sources in case surface water is not saline and iii) in regions where agriculture relies on groundwater since surface water is too saline, a shift to more saline tolerant crops or other agro-ecosystems (Renaud *et al.*, submitted) should be considered in order to save groundwater sources for drinking purposes.

Nutrients

The concentrations of NO_2 and NO_3 did not exceed drinking water guidelines in any samples in this study. This finding is in line with Buschmann *et al.* (2008) who also found low NO_3 concentrations (< 0.2 mg L^{-1}) in groundwater in southern Vietnam and Cambodia. Instead, most of the nitrogen compounds were present as NH_4. These high concentrations could be explained by the mineralization of organic rich materials in the soil under strongly reduced environments (Böhlke *et al.*, 2006). In addition, anthropogenic activities such as leaching of fertilizers, organic waste disposal and leaking sewage systems could also contribute to the high concentrations of NH_4 in groundwater (Lindenbaum, 2012). Although NH_4 does not have direct health-related impacts on humans, this nutrient was found to negatively affect disinfection of water by chlorine at concentrations >0.1 mg L^{-1}. At NH_4 concentrations >15 mg L^{-1}, chlorine is almost completely transformed to chloramine which is a less effective disinfectant (Duong *et al.*, 2003). Moreover, there is a risk that NH_4 could be converted to NO_3 in water supply systems when the water comes into contact with oxygen. Therefore, a guideline level for NH_4 is established in many (international) drinking water standards such as in the European Union which has set a guideline for drinking water of 0.5 mg L^{-1} (EU, 1998).

Phosphates and sulphates do not have significant health-related risks. Nevertheless, drinking water guideline values for SO_4 are defined at concentrations >500 mg L^{-1} which refers to a concentration level at which the taste of the water impacts consumption (WHO, 2004b). The highest percentage of samples exceeding guidelines values for SO_4 are, similar to NH_4, found in the coastal areas. The presence of SO_4 could be explained by natural occurrence in the soil in the form of e.g. sodium, potassium and magnesium sulphates (WHO, 2004b).

Arsenic and other metal(loid)s

The concentrations of As exceeded drinking water guidelines for 2% and 9% of samples in the coastal and inland regions, respectively. Positive correlations between As with Fe and o-PO_4 were found. The occurrence of As in groundwater could be explained by the reduction of As- and o-PO_4-rich iron-bearing minerals which is also recognized as arsenic source in a variety of other studies in the Mekong River basin (Nickson *et al.*, 2000; McArthur *et al.*, 2001; Buschmann *et al.*, 2008; Hoang *et al.*, 2010). This process may also explain the generally high Fe concentrations in groundwater in our study sites. However, beside this reductive dissolution of As- and Fe-bearing host minerals leading to mobilization of arsenic, the process is likely controlled by local, small-scale mineralogy of subsurface sediments and the presence of organic matter as an electron donor in microbially-mediated reduction processes (Reyes *et al.*, 2008). Thus, arcenic is mobilized under different conditions in groundwater. Buschmann *et al.* (2008) found significant relationships between As and PO_4, NH_4, Dissolved Organic Carbon (DOC) while Hoang *et al.* (2010) detected significant relationships between As and pH, TOC and Mn. Moreover, Kurosawa *et al.* (2013) found positive correlations between As and NH_4 concentrations in groundwater in Southeast Asia while Buschmann and Berg (2009) found that a sufficient supply of SO_4 will inhibit the release of As in groundwater. Although our study also showed significant correlations between As and pH and o-PO_4 (inland region), this was not observed for NH_4, SO_4, TOC and Mn. In our study sites, As was instead correlated with NO_2, NO_3 and Cl which emphasizes the role of local processes in the release of As and could be linked for example with groundwater withdrawal and the infiltration of organic carbon rich surface water (Lawson *et al.*, 2013). The intensive groundwater withdrawal for drinking purposes for example in Can Tho City might explain the potential hot-spot area of As (Fig. 17c_2). The concentrations of As and Fe were also positively correlated to turbidity levels. This could be explained by the fact that during sample collection, oxygen from the air mixed with the naturally anoxic groundwater which leads to corrosion of iron compounds. The weak significant relationship between As and well depths (Fig. 16) suggests that slightly higher As concentrations can be expected at deeper wells. This finding is in line with Erban *et al.* (2013) who found that mean As concentrations in shallow aquifers (Holocene-Pleistocene) were lower compared to deeper wells in the Pliocene-Miocene (4 vs. 20 µg L^{-1}, respectively) in the MD.

Mn is an essential nutrient for humans and animals. However, the presence of Mn in drinking water sources could lead to severe health risks like neurotoxicity for children, although the exact concentration limits were difficult to determine (Wassermann *et al.*, 2006). The presence of Mn in groundwater of the MD is widespread and could be found at almost all locations at concentrations exceeding drinking water guidelines in the inland region (Fig. 17d_2). This finding is in line with Buschmann *et al.* (2008) who concluded that the distribution of Mn in groundwater of the MD is by far not homogenous. Also Fe concentrations in groundwater (not presented in maps) show a similar pattern as Mn. Both Mn and Fe are metals that are naturally present in soils. However, the concentrations in groundwater are dependent on the redox potential and to a lesser extend on pH (Ahmad, 2012). The generally higher pH values in the coastal region compared to the inland region could explain the lower Mn and Fe concentrations in the coastal region.

The consumption of barium-rich drinking water may cause health concerns like vasoconstriction and potentially affects blood pressure (WHO, 2004a). Ba exceeded drinking water guidelines set by the WHO for 1% and 7% of the samples in the coastal and inland regions respectively. The observed concentrations in our study are in line to those of Shinkai *et al.* (2007) who also found Ba concentrations between 200 – 800 µg L^{-1} in the MD. The presence of Ba in groundwater could be explained by the dissolution of barite ($BaSO_4$) by sulphate reducing bacteria (Moore and Staubitz, 1984). This finding is in line with Buschmann *et al.* (2008) who also found that the main source of Ba in groundwater was caused by $BaSO_4$ reduction. However, in our study we found an inverse relationship between Ba and SO_4 concentrations. This could be explained by the activity of sulphate reducing bacteria. Under anoxic conditions, as is most probably the case in groundwater bodies in the MD, these bacteria use sulphate as oxygen source to metabolize organic materials which results in the reduction of sulphate to sulfide (Moore and Staubitz, 1984).

Despite similarities between studies regarding observed concentrations and causes of pollution for As and other metal(loid)s in the groundwater of the MD, major differences were also found. This suggests severe local variability in chemical/biological reactions leading to different concentrations of metals in groundwater bodies of the MD. However, different well depths in various regions are also an important parameter that defines the quality of pumped groundwater. Due to strong local variability of observed groundwater quality, it is difficult to predict groundwater quality for other regions outside the selected study areas. It is therefore important to assess the quality of groundwater in Southeast Asian regions that have not been investigated to date but are intensively used as drinking water source.

Bacterial water quality

Fecal indicator bacteria were detected in groundwater sources and may lead to severe health-related concerns in the MD. The presence of *E. coli* and total coliform bacteria in groundwater could be caused by leakage from septic tanks and sewage systems and leaching of water from the surface areas to groundwater via rainfall infiltration. Canals and rivers could also directly contribute to bacteriological contamination of groundwater. Especially shallow groundwater is expected to be heavily contaminated since this water is in close contact and thus very vulnerable to these surface-related pollution sources. However, the selected groundwater wells in our study are drilled in the second aquifer (Pleistocene). The presence of pathogens was not expected in this aquifer since it is separated and protected from surface-related pollution sources by thick layers of clay and silt (aquitard). Nevertheless, *E. coli* was detected in 5% of the samples while total coliforms were detected in 33% and 38% of samples collected for the inland and coastal region respectively. No significant relationship was found between coliform counts and well depth which may confirm that surface-related pollutants are not related to the microbial pollution of our selected groundwater samples. Instead, the presence of microbial indicator bacteria in the selected groundwater wells could be explained by: i) poorly maintained pumps. It was observed that many groundwater pumps lacked vacuum necessary for suction probably due to poor maintenance. Therefore, people fill the well with external water sources like river water prior to pumping. This will most likely cause severe microbial pollution in deeper groundwater sources since surface water contains high concentrations of *E. coli* and total coliforms (Wilbers *et al.*, 2014); ii)pollution from top-soils into the borehole. During the drilling of a borehole, external pollution can enter the deeper groundwater layers. This is especially a risk for new groundwater wells since the borehole can still contain microbiologically polluted particles from the top-soil.

The detection of pathogens in groundwater sources in the MD confirms results from Isobe *et al.* (2004) and Leber *et al.* (2011) who also found *E. coli* in household used groundwater in the MD and in Bangladesh respectively. Leber *et al.* (2011) found that in 12% of the deeper wells (>20 meters) *E. coli* was present. Isobe *et al.* (2004) detected *E.coli* in six out of nine sites although well depths were not recorded. Based on these findings it is recommended to focus on proper management and maintenance of household groundwater wells via i.e. educational programmes in order to prevent and/or reduce water-borne diseases from groundwater consumption.

5.4.3 Hot-spot areas of pollution

Groundwater sources are intensively used as a drinking water source in both rural and urbanized areas of the MD. However, at some locations, this drinking water source has elevated concentration of Cl, nutrients, metals and pathogens that make groundwater unsuitable for drinking potentially affecting human health. The maps could be used to assist decision makers where groundwater should be extracted for drinking, domestic and irrigation purposes. Moreover, the maps indicate what kind of water treatment may be required to become potable.

Microbial indicator bacteria concentrations were not selected for risk mapping since the presence of indicator bacteria in groundwater is most likely not related to spatial factors but to management and maintenance practices of household wells. Therefore, groundwater could potentially be polluted with fecal indicator bacteria at all locations and should therefore always be treated (e.g. via boiling) prior to drinking.

5.5 Conclusions

Groundwater extracted at household level from the upper-middle Pleistocene aquifer of the MD exceeds drinking water guidelines for various water quality parameters in both inland and coastal regions. Due to continuous over-exploitation and to potential consequences of other anthropogenic influences, the risk of salinity intrusion into groundwater bodies is expected to increase in the near future. Desalinization techniques may be too expensive for wide-spread use in the MD. Therefore, it is recommended to carefully manage groundwater sources in order to sustain them for future generations.

Groundwater is frequently extracted at household level and used without any further treatment in the MD. However, as shown in this study, water quality deserves more attention and treatment in many areas of the delta. The metals As, Ba, Fe and Mn were found to exceed drinking water guidelines. High concentrations of these metals will make groundwater unsuitable for drinking due to poor taste, smell and color (Fe and Mn) and / or cause severe health risks (As, Ba, Mn). Therefore it is recommended to treat groundwater with i.e. sand filters prior to drinking. Responsible agencies should consider developing educational programmes for rural communities to raise awareness regarding microbial contamination of groundwater, even when the water “looks clean and safe”. Possible causes of microbial contamination in groundwater, such as poor maintenance of the pump, should be addressed in order to prevent microbial contamination. Furthermore, disinfection of groundwater is required and should be done preferably by boiling. Disinfection with chlorine is less effective due to generally high NH_4 concentrations in groundwater bodies of the MD.

Despite the repeatedly mentioned health-related concerns regarding the consumption of groundwater, spatial risk-maps show large areas in both inland and coastal regions with groundwater of good quality. Therefore, the development and consultation of groundwater quality risk-maps could be useful for decision makers to assist them in defining areas where groundwater is suitable for drinking. Furthermore, such maps could indicate what kind of water treatments are required in order to make groundwater potable for the selected sites in the MD. In general, if groundwater sources are used sustainably, the resource can provide safe drinking water supplies for both present and future generations. Groundwater has a main advantage above piped-water since it is not dependent on a large pipe system which may leak or be contaminated. Furthermore, piped-water supply stations often provide water irregularly due to broken systems and/or power cuts. Moreover, groundwater can be considered as a safer drinking water source compared to surface water which is considerably contaminated by industry, urban agglomerates and agricultural activities. Rainwater on the other hand is usually not available throughout the year. Although groundwater seems to be a decent drinking water source, if appropriately extracted and treated, it is also necessary to further investigate the presence of pesticides and antibiotics in groundwater since these substances can also cause severe health-related risks when present in elevated concentrations.

6. Piped-water supplies in rural areas of the Mekong Delta, Vietnam: water quality and household perceptions

Abstract

In the Mekong Delta (MD) in Vietnam, piped-water supply stations are being intensively built to reach the millennium development goal (MDG) to provide safe and clean drinking water sources to communities. However, studies focusing on the effectiveness of supply stations in reaching these goals are scarce to date. Water samples from 41 water supply stations in the MD were collected between June and October 2012. Water samples were analyzed for general parameters, salinity, nutrients, metal(loid)s and microbial indicator bacteria and compared with World Health Organization (WHO) and Vietnamese drinking water guidelines. In addition, 542 household interviews were conducted to investigate the connection rate to piped-water and people's perceptions regarding piped-water supplies. The results show that water guidelines were exceeded for pH (min. 6.2), turbidity (max. 10 FTU), Cl (max. 1,576 mg L-1), NH_4 (max. 7.92 mg L-1), Fe (431.1 µg L-1), Hg (11.9 µg L-1) and microbial indicator bacteria (max. total coliform 50,000 CFU 100 mL-1). Moreover, more than half of the interviewed households with access to a piped-water supply did not use this supply as a source of drinking water due to i) high connection fees, ii) preference for other water sources and iii) perceived poor quality/quantity. Our study shows that the maintenance and distribution of water supply stations should significantly improve in order for piped-water to become a reliable drinking water source. Additionally, alternatives such as rainwater harvesting and decentralized treatment facilities should also be considered.

6.1 Introduction

One of the Millennium Development Goals is that by 2015, the population without sustainable access to safe drinking water and basic sanitation should be halved (United Nations, 2000). The Mekong Delta (MD) in Vietnam is a region where access to and availability of safe drinking water supplies are limited to date. In the region, shallow household groundwater wells are commonly present but are often contaminated with arsenic (As) and other metals (Hoang *et al.*, 2010). Surface water is also widely available but is intensively polluted by nutrients, agrochemicals and microbial contaminants (Toan *et al.*, 2013; Sebesvari *et al.*, 2012). Rainwater is another popular drinking water source, although most people do not have sufficient storage capacity to supply water-year round (SNV, 2010) and the quality is often deteriorated by a variety of factors including unhygienic post-harvest practices (Wilbers *et al.*, 2013). As a result, Vietnam has a high rate of water-borne diseases. For example, 8.5% of all deaths are caused by diarrhea, which is likely to be partially related to inadequate water quality (WHO, 2013b). Access to safe and clean water is therefore a priority in the region and water supply facilities are considered to be a main solution to this problem, as stated in the National Target Program for Rural Water Supply and Sanitation (MARD, 2005). This program is sponsored by a variety of countries and its aim is to provide access to safe and clean water for 85% of the rural population in Vietnam by 2015 (AusAID, 2012). In contrast, to date, less than 10% of the rural population in Vietnam is connected to piped-water supply systems (SNV, 2010). The importance of piped-water supplies in achieving an improvement in the health conditions of the rural population is emphasized in a variety of studies. Esrey *et al.* (1991) found a reduction in morbidity for various water-related diseases, such as diarrhea and dracunculiasis, due to improved water supplies and sanitation world-wide. A study in the rural areas of the MD found that people connected to piped-water benefited from better water quality and improved water availability while the risk of diarrhea was reduced in comparison with households that used other water sources (Brown *et al.*, 2013). Furthermore, it was found that the development of water supply systems is generally economically beneficial due to time savings (no water collection needed) and reduced illness and mortality (Hutton *et al.*, 2007). However, other studies mention concerns regarding the role of piped-water supply networks as the only solution to overcome clean water supply problems. Reis and Mollinga (2009), for example, found that some households in the rural areas of the MD did not connect to piped-water even when the networks were available, either due to their preference for other water sources or their inability to pay the connection fee or both. According to Carter *et al.* (1999), water supply systems in developing countries are often under-utilized, broken down or abandoned and that time-savings and health impacts remain limited. Furthermore, in Vietnam 40% – 80% of water supply systems were found to be broken due to poor construction and natural disasters (SNV, 2010). Tran *et al.* (2010) reported problems regarding piped-water, including low reliability of water supply, high costs, and water quality aspects such as odor, taste and turbidity. These concerns are why many households prefer other water sources or store piped-water in jars and tanks prior to usage, leading to an enhanced risk of malaria and dengue due to the increased occurrence of habitats for mosquito larvae.

In this study, piped-water is defined as tap water from the distribution lines of a piped-water supply station. In general, this water source is considered to be a solution to providing safe (drinking) water to people in the rural areas of the MD by (inter)national authorities. However, studies on the quality of the water supplied by these stations are scarce to date. Water supply stations use either groundwater or surface water and apply various treatment techniques including sand and rock filtration, alum addition, chlorination and in some cases active coal. However, the quality of piped-water cannot *a priori* be assumed to be better than its original sources when treatments are poorly applied or when maintenance of supply stations is limited, which, based on the literature, could be a main concern in the MD. Moreover, it was found that the connection rate of rural people in the MD to piped-water networks is still insufficient to date (Reis and Mollinga, 2009). Therefore, many people still rely on completely untreated or insufficiently treated water sources for domestic use and drinking water, such as surface water. The objectives of this study were therefore to: i) investigate the piped-water quality from different sources (surface water and groundwater) for general parameters, Cl, nutrients, metal(loid)s and microbial indicator bacteria and compare results with (inter)national drinking water guidelines; ii) assess spatial differences in piped-water quality; iii) compare piped-water quality with the quality of untreated water sources in order to assess the efficiency of applied treatments and iv) assess reasons for the low connection rate to piped-water supplies in rural areas of the MD. In this study, we describe the current status of piped-water supply stations in the MD, which is of interest to decision makers in order to improve management strategies. Furthermore, this study can be used to evaluate whether and how water supply stations contribute to safe water supplies for rural populations in this Southeast Asian region.

6.2 Materials and Methods

6.2.1 Study area

The MD is located in the south of Vietnam. Water samples were taken close to supply stations in the three delta provinces Can Tho, Hau Giang and Soc Trang (Fig. 18).

The region has a tropical climate that is influenced by the southwestern monsoon, which generates dry and wet seasons (MRC, 2005). The MD is dominated by agricultural activities and is considered as the ‘rice granary’ of Vietnam. Other agricultural activities like fruit orchards, aquaculture and upland crops are also common in the MD (GSO, 2012b). The total population was 17.3 million in 2011 (GSO, 2011). The MD has a dense network of waterways including rivers, main canals and a variety of lower order canals. Most people in the MD live along these waterways and thus most houses are widely dispersed across the region. However, along rivers and intersections of main canals people settle in larger villages and cities. Since surface water is commonly available at most locations, this resource is used for a variety of functions including drinking, especially in rural areas that are not influenced by salinity intrusion. Other popular drinking water sources in the rural areas include groundwater, especially since the 1990s (Wagner *et al.*, 2012), and harvested rainwater, while in (larger) villages and cities most people are connected to piped-water sources. In rural areas of the MD, piped-water supplies are also available at some locations.

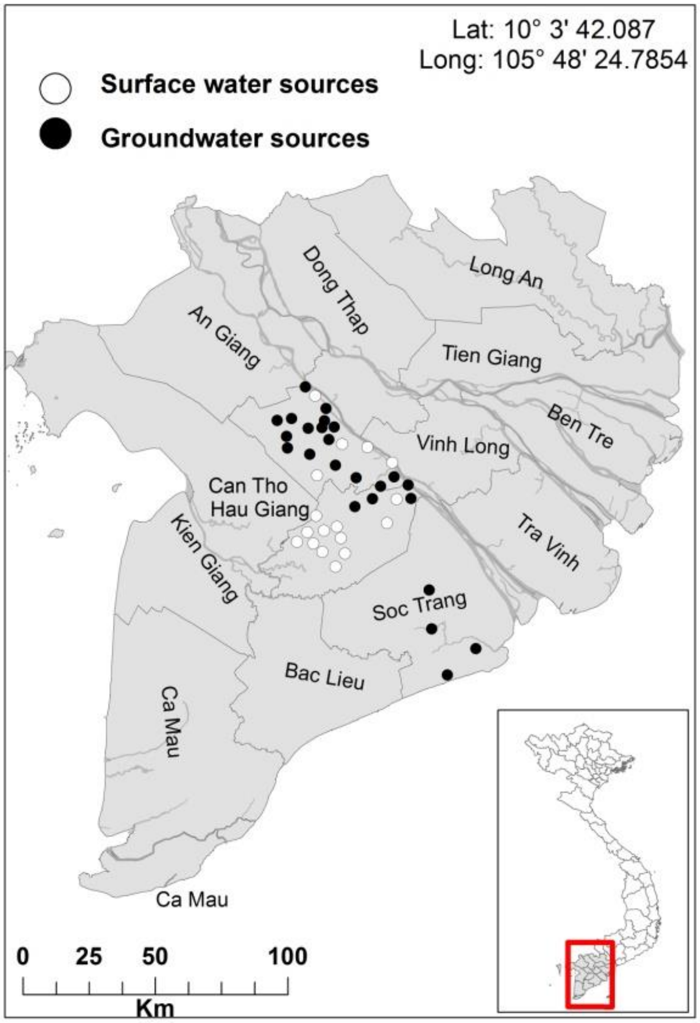


Figure 18 – Overview of the MD and the selected water supply stations for water quality analysis. The white dots indicate water supply stations that use surface water sources while the black dots represent supply stations that use groundwater sources.

6.2.2 Water sampling and analytical procedures

Piped-water samples were collected in 2012 in the rainy season from June to October, as part of a larger monitoring program of drinking water sources in the MD. In total, 41 water supply stations were selected in various regions of Can Tho, Hau Giang and Soc Trang provinces in order to achieve good spatial representation and sufficient coverage for stations with both groundwater and surface water as intake sources. These provinces were selected as representative study areas of the MD based on land-use characteristics (rice, orchards, aquaculture, urbanization/industrialization) and hydrology (inland versus coastal areas) since investigating supply stations in the entire MD was too difficult, due to its large surface area (around 39,000 km^2). Initially, a desk-based study allowed for the identification of sampling locations and these were subsequently localized in the field by GPS (Garmin eTrex, Olathe, KS, USA). Sampling locations were selected with the aim of achieving a representative coverage of the selected provinces. A working water supply station near the predefined location was then selected. However, a water supply station could only be assessed when it was possible to interview the water supply manager and permission was given to enter the water treatment plant. Even with such permission, sampling at the station was still a sensitive issue; thus the samples were taken directly from the tap of the household closest to the station, which was usually a few meters away from the supply station. Prior to sampling, water supply managers were asked to provide information regarding applied treatments and the intake water source. The supply stations were also visited to assess treatment facilities and the intake point. Four water supply stations were selected in Soc Trang province, whereas 37 locations were selected in Can Tho and Hau Giang provinces (Fig. 18). Only four locations in Soc Trang were selected due to relatively long travel times from this area to laboratory facilities in Can Tho City. Samples were analyzed for general parameters (Electrical Conductivity (EC), pH and turbidity), Chemical Oxygen Demand (COD), chloride (Cl), nutrients (ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), ortho-phosphate (o-PO_4)), metal(loid)s (total arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), zinc (Zn) and magnesium (Mg)) and for microbial indicator bacteria (*E. coli* and total coliforms). 250 ml polyethylene (PE) bottles were used to store water for EC, pH, turbidity, COD, Cl and nutrient analysis. 50 ml PE bottles were filled with water samples and acidified with 1% nitric acid (65%, Merck Millipore, Billerica, MA, USA) for metal analysis. Sterilized 100 mL glass bottles were used to store water for microbial analysis. All samples were cooled with ice and stored in the dark during transportation and delivered to the laboratory within 8 hours of sampling. Electrical conductivity and pH were measured with a WTW Multi 340i (Weilheim, Germany) probe in the laboratory within 24 hours of sampling. For COD, Cl and nutrient analysis, all samples were stored at 5 °C, pre-treated by syringe filters (0.45 µm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 hours. COD was analyzed with the reactor digestion method TNTplus^{TM} low range 3 – 150 mg L^{-1} (Hach, Loveland, CO, USA), while Cl was measured by Spectroquant ® cell tests with range 2.5 – 250 mg L^{-1} (Merck Millipore, Billerica, MA, USA). For the nutrients, NO_3, NO_2 and o-PO_4 were measured using Merck Millipore Spectroquant ® cell tests with the following ranges: NO_3-N: 0.5 – 18.0 mg L^{-1}; NO_2-N: 0.002 – 1.000 mg L^{-1}: PO_4-P: 0.05 – 5.00 mg L^{-1} (Merck Millipore, Billerica, MA, USA). NH_4 was measured with Nitrogen-Ammonia Reagent Set, Test 'N tube' with range 0.2 – 2.5 mg L^{-1} (Hach, Loveland, CO, USA). Samples for metal analysis were stored in a fridge at 5°C and analyzed within three months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA). Samples for microbial analysis were treated within 8 hours of sampling under sterile conditions by plating 1 mL of sample water on 3M^{TM} petrifilm^{TM} coliform count plates (3M, St. Paul, MN, USA) with replication (n=2). *E. coli* and other coliform colonies were counted 24±4 hours after incubation at 37ºC. In order to assess water treatment efficiency, the quality of piped-water samples from stations extracting surface water were compared with the quality of 223 untreated surface water samples that were collected in the same region and time-span as the selected piped-water samples (Wilbers *et al.*, 2014). A comparison between piped-water extracted from groundwater and untreated groundwater was not performed, since no untreated groundwater samples from the locations and well depths that were used by the water supply stations (well depths 100 – 350 m) were available.

6.2.3 Household interviews

A total of 542 households were interviewed in the rural areas of Can Tho, Hau Giang and Soc Trang provinces. Several districts in these provinces were selected in order to cover the entire study region as optimally as possible. Moreover, the selected districts were in the same region as the selected water supply stations. After arrival at the selected districts, rural households were randomly interviewed with the following constraint: the minimum distance between two households was 500 meters, in order to prevent interviewing similar type households (e.g. a cluster of households connected to a piped-water supply station might not be representative for the region). Amongst other purposes, the interviews aimed to assess the availability, usage, and households' perceptions of piped-water supplies. Selected households were asked which water sources (surface-, ground-, rain-, bottled-, and /or piped water) they used for drinking and for domestic purposes such as washing, cleaning, dishwashing etc. In addition, households were asked i) whether a connection to a piped-water supply station was available and ii) whether this source was used for domestic or drinking purposes or both. If piped-water was used, a series of open questions was asked regarding the volume of piped-water used per month and how the quality of the piped-water was perceived. If piped-water was not used, despite being available, questions were asked to clarify the reasons for non-use. The monthly income of households was also assessed.

6.2.4 Data analysis

Water quality from selected piped-water supply stations was compared with drinking water guidelines set by the World Health Organisation and the Vietnamese Government (WHO, 2011; Ministry of Health, 2009). Statistical tests were carried out with SPSS version 20.0. The differences in piped-water quality from stations using surface- and groundwater sources respectively were statistically assessed by applying the Mann-Whitney-U test. A non-parametric test was applied, due to the unequal amount of samples between datasets, the presence of outliers and the lack of normal distribution, which was verified with the Shapiro-Wilk test. The Mann-Whitney-U test was also applied to assess for significant differences between the quality of piped-water and the quality of untreated surface water, since the datasets were of unequal size and also lacked a normal distribution. Spatial differences in piped-water were assessed visually by plotting the piped-water stations that exceeded guidelines on maps. The results of the household interviews regarding availability and usage of piped-water sources are presented graphically.

6.3 Results

6.3.1 Piped-water quality

Although piped-water is expected to be a safe drinking water source, some water quality parameters were found to exceed the drinking water guidelines set by the World Health Organization (WHO) and the Vietnamese Government (VG) (WHO, 2011; Ministry of Health, 2009) (Table 15). The quality of piped-water was also found to be dependent on the original source (groundwater or surface water).

Significantly higher EC and pH levels were found in water from supply stations using groundwater compared with those using surface water. WHO and VG water quality guideline values for pH were exceeded in supply systems with both surface and groundwater intakes. Turbidity levels were also found to exceed the guideline values, although no significant difference was observed between supply systems using different water sources. Water quality guidelines for Cl were exceeded in 18% of the water supply stations with groundwater intake, whereas supply stations with surface water intake did not exceed the guidelines set by WHO and VG. For nutrients, the concentrations of NO_2 and NO_3 in all samples were low in piped-water when compared with guideline values. Relatively high concentrations of NH_4 were found for some supply stations with groundwater intake but overall there was no significant difference in median NH_4 concentrations between the water supply systems with different intake sources. For metals, the concentrations of As, Ba, Cd, Mg and Zn were significantly different between the two types of supply systems, although WHO and VG drinking water guidelines were not exceeded for any of the samples. In general, most of the piped-water samples investigated showed metal(loid) concentrations close to or below detection limit. However, Fe exceeded WHO and VG drinking water guidelines for 8% of the samples from piped-water with groundwater intake. Hg was detected in some piped-water samples for supply stations with surface- and groundwater intake. Values for Hg exceeded both WHO and VG guideline, VG levels being considerably more stringent than those of the WHO. Microbial indicator bacteria were also detected in some piped-water samples indicating that drinking this water can lead to health-related risks. No significant differences in microbial indicator bacteria cell counts were observed between the two types of supply stations.

Table 15

Piped-water quality for 41 water supply stations in three provinces of the Mekong Delta (Can Tho, Hau Giang and Soc Trang). The stations were classified depending on the water source they use for intake. Significant differences in piped-water quality between stations using groundwater and surface water sources are assessed by the Mann-Whitney-U test and vizualized bz Z-values.

	WHO[a]	Vietnam[b]	Groundwater source					Surface water source					Statistical difference
	Guidelines	Guidelines	N	Median	Min	Max	%WHO - Vietnam[c]	N	Median	Min	Max	%WHO - Vietnam[c]	Z-value
Phy.chem. Parameters													
EC (dS m^{-1})	-	-	19	1072	110	2190	-	16	158	98	199	-	**-4.54**[#]
pH (-)	6.5-8.5*	6.5-8.5	22	7.6	6.2	8.3	5 - 5	9	7.0	6.3	7.3	11 - 11	**-2.55**[#]
Turbidity (FTU)	5*	2	24	2.5	0	8	13 - 54	17	3	0	10	6 - 71	-0.78
COD (mg L^{-1})	-	-	24	3.2	<3.0	8.3	-	17	<3.0	<3.0	9.2	-	-0.43
Salinity													
Cl (mg L^{-1})	250*	250	22	73	<2.5	1576	18 - 18	12	18	9	21	0 - 0	**-3.59**[#]
Nutrients													
NH$_4$ (mg L^{-1})	0.5 (EU)[d]	-	24	0.07	<0.02	7.92	21 -	17	<0.02	<0.02	0.09	0 -	-1.29
NO$_3$ (mg L^{-1})	50	50	24	0.6	<0.5	2.0	0 - 0	17	1.0	0.5	2.9	0 - 0	**-2.42**[#]
NO$_2$ (mg L^{-1})	3	3	24	0.004	<0.002	0.078	0 - 0	17	0.005	<0.002	0.011	0 - 0	-0.16
o-PO$_4$ (mg L^{-1})	-	-	22	0.15	<0.05	0.32	-	9	0.05	<0.05	0.14	-	**-2.97**[#]
Metal(loid)s													
As (µg L^{-1})	10	10	24	2.1	<2.0	8.2	0 - 0	17	<2.0	<2.0	2.3	0 - 0	**-2.82**[#]
Ba (µg L^{-1})	700	700	24	112.3	12.2	316.3	0 - 0	17	17.8	6.9	43.6	0 - 0	**-4.76**[#]
Cd (µg L^{-1})	3	3	24	<0.1	<0.1	0.6	0 - 0	17	<0.1	<0.1	0.3	0 - 0	**-2.16**[#]
Cr (µg L^{-1})	50	50	24	<0.4	<0.4	<0.4	0 - 0	17	<0.4	<0.4	<0.4	0 - 0	0.00
Cu (µg L^{-1})	2.000	1.000	24	1.1	<0.3	12.9	0 - 0	17	2.1	0.3	12.3	0 - 0	-1.19
Fe (µg L^{-1})	300*	300	24	24.4	3.0	431.1	8 - 8	17	26.6	7.3	163.8	0 - 0	-0.29
Hg (µg L^{-1})	6	1	24	1.2	<1.2	11.9	13 - 42	17	<1.2	<1.2	4.3	0 - 24	-1.62
Mn (µg L^{-1})	400	300	24	7.1	0.3	193.5	0 - 0	17	2.9	<0.3	297.3	0 - 0	-1.03
Ni (µg L^{-1})	70	20	24	<0.4	<0.4	1.4	0 - 0	17	0.4	<0.4	2.6	0 - 0	-1.76
Zn (µg L^{-1})	3000*	3.000	24	2.9	<0.1	13.2	0 - 0	17	7.0	<0.1	84.0	0 - 0	**-2.32**[#]
Mg (mg L^{-1})	-	-	24	12.0	0.1	48.0	-	17	4.1	1.7	6.3	-	**-3.78**[#]
Microbial indicators													
E.coli (CFU 100 mL^{-1})	0	0	24	0	0	100	12 - 12	17	0	0	0	0 - 0	-1.50
Total coli. (CFU 100 mL^{-1})	0	0	24	100	0	50,000	54 - 54	17	0	0	1400	29 - 29	-1.43

[a] World Health Organization guideline for drinking-water quality for chemicals of health concern (WHO, 2011)

[b] Drinking water quality guidelines set by the Ministry of Health in Vietnam (Ministry of Health, 2009)

[c] Percentages of piped-water samples that exceeds the World Health Organization and Vietnamese drinking water guideline respectively

[d] European Union quality guidelines for water intended for human consumption (EU, 1998)

* Secondary drinking water guidelines by World Health Organization that are not a direct health-risk (WHO, 1996)

N: Number of samples; -:no guideline value set

[#] Significant different concentrations ($p < 0.05$)

NB: the amount of samples for o-PO$_4$, Cl, pH and EC are lower compared to other investigated parameters due to limited capacity in analysis equipment

6.3.2 Visualization of the spatial distribution of stations supplying contaminated water

Spatial presentation of the piped-water quality was performed to easily spot water supply stations where piped water quality exceeds drinking water guidelines (Fig. 19). For the presentation of guideline exceedance on maps, the WHO drinking water standards were selected as they represent an international standard and can be compared with other regions around the world.

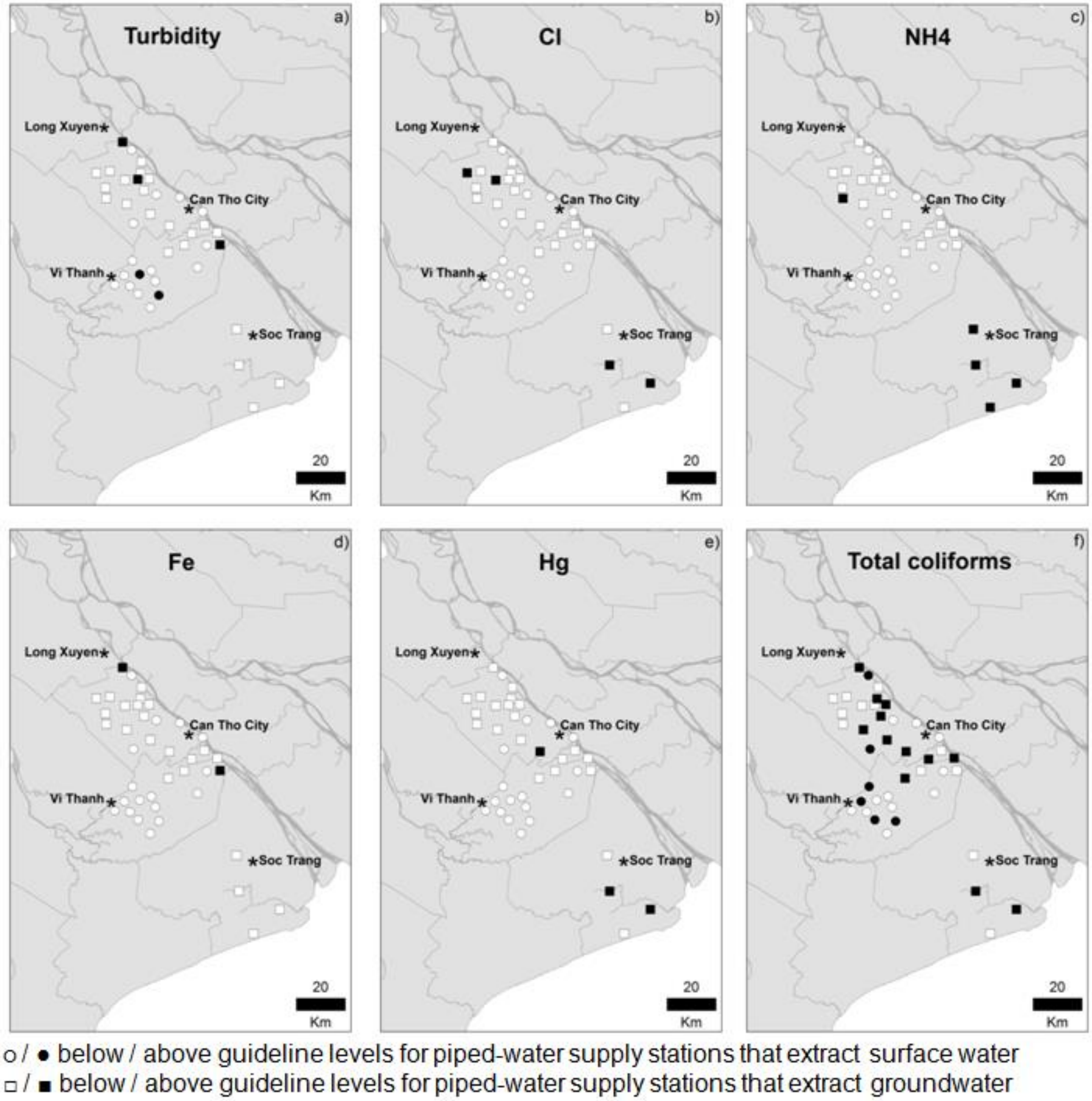


Figure 19 – Spatial representation of water supply stations exceeding drinking water guidelines indicated by black boxes and dots for a) turbidity level, b) chloride, c) ammonium, d) total iron, e) mercury and f) total coliforms

The maps show that in coastal regions, piped- water supplies were exclusively taken from groundwater sources. In southern areas of the inland region (Vi Thanh), only surface water was used. In the other regions (between Long Xuyen – Can Tho City) surface- and groundwater were both used for piped-water supplies. For turbidity levels (Fig. 19a) and total coliform cell counts (Fig. 19f), no spatial relationships were observed between locations and extraction sources, which indicates that guideline exceedance for these parameters can be observed randomly in the study areas. In contrast, concentrations of Cl and NH_4 (Fig. 19b,c) mostly exceeded drinking water guidelines at supply stations in the coastal region and only for stations using groundwater. The quality of groundwater that water supply stations use for extraction should be further investigated to assess the causes of elevated Cl and NH_4 concentrations. Two supply stations using groundwater in the inland regions exceeded drinking water guidelines for Fe, although this pattern was not observed for supply stations using surface water (Fig. 19d). Two water supply stations in the coastal region exceeded drinking water guidelines for Hg, while this was only the case for one station in inland regions. However, all three supply stations exceeding Hg guidelines used groundwater sources. Three water supply stations had multiple water quality concerns (not shown on the map). One station located east of Can Tho City exceeded guidelines for turbidity, Fe and total coliforms. Two stations in the coastal region exceeded guidelines for Cl, NH_4, Hg and total coliforms.

6.3.3 Applied water treatments

Water supply stations apply various treatment techniques before supplying the water to the local communities. Interviews with water supply managers at the selected stations revealed that water is generally treated by rock and sand filters in combination with disinfection (chlorine), although at one site active coal is used. Water supply companies using surface water additionally apply a chemical treatment step with alum to remove suspended particles. After treatment, the water is usually stored in water towers from where it is distributed to the connected households. The effects of these treatments are clearly visible when the quality of piped-water extracted from surface water is statistically compared with the quality of untreated surface water (Table 16). A comparison of the quality of piped-water from groundwater intake with untreated groundwater was not possible due to a lack of deep groundwater quality data.

For surface water sources, EC and turbidity levels, as well as COD, were significantly lower in piped-water compared with untreated surface water. However, this pattern was not observed for pH values. Cl was found not to be removed by water treatment systems at all. Concentrations of NH_4, NO_2 and o-PO_4 were strongly reduced by the water treatment systems while NO_3 concentrations were slightly higher after treatment. Generally, concentrations of metal(loid)s in surface water, especially Cr, Fe, Mn and Ni, were significantly reduced by treatment at water supply stations. The concentrations of Cu and Zn were not significantly reduced by the treatment steps but concentrations did not exceed drinking water guidelines. Microbial contaminant concentrations were also significantly reduced by treatment, although *E. coli* and total coliform guidelines were still exceeded at some supply stations (Fig. 19f).

Further investigation of the influence of separate treatment processes on water quality in order to assess the efficiency of the removal of pollutants in water is recommended.

6.3.4 Household interviews

In total, 39% of households interviewed had potential access to piped-water distribution systems (Fig. 20). In contrast, the other households (61%) had no possible access to piped-water, since a water supply station was not present or was not operational.

Of the households with possible access to a piped-water supply station, 27% preferred not to connect to the water supply station and used other water sources, such as groundwater for daily purposes. 30% of those with access were connected to the supply station but only used the water for domestic purposes like washing and cleaning rather than for drinking. The remaining residents (43%) with possible access to piped-water indicated that they drank piped-water and were generally satisfied with the quality of this water source, although these households also mentioned concerns regarding irregular water supply. Overall, less than 50% of all households with a potential access to the water supply system used this source for drinking purposes.

Table 16

Median levels/concentrations of piped-water and untreated surface water in the selected study areas. Significant differences between the quality of piped-water with untreated surface water sources are visualized by calculated Z-values using the Mann-Whitney-U test.

	Surface water		
	Untreated source[a]	Piped-water surface water[b]	Statistical test (Z-value)
Phy.chem. Parameters			
EC	180	158	**-2.04**[#]
pH (-)	6,8	7.0	-1.43
Turbidity (FTU)	98	3	**-6.87**[#]
COD (mg L^{-1})	22	<3.0	**-6.46**[#]
Salinity			
Cl (mg L^{-1})	18	18	-0.08
Nutrients			
NH_4 (mg L^{-1})	0.7	<0.02	**-6.81**[#]
NO_3 (mg L^{-1})	0.5	1.0	**-4.04**[#]
NO_2 (mg L^{-1})	0.047	0.005	**-6.43**[#]
o-PO4 (mg L^{-1})	0.20	0.05	**-4.55**[#]
Metal(loid)s			
As (µg L^{-1})	2.6	<2.0	**-4.43**[#]
Ba (µg L^{-1})	41.6	17.8	**-4.92**[#]
Cd (µg L^{-1})	0.2	<0.1	**-3.95**[#]
Cr (µg L^{-1})	5.0	<0.4	**-6.57**[#]
Cu (µg L^{-1})	3.4	2.1	-1.74
Fe (µg L^{-1})	2873.9	26.6	**-6.57**[#]
Hg (µg L^{-1})	1.6	<1.2	**-2.50**[#]
Mg (mg L-1)	5.5	2.9	**-3.51**[#]
Mn (µg L^{-1})	324.2	0.4	**-5.72**[#]
Ni (µg L^{-1})	3.0	7.0	**-6.18**[#]
Zn (µg L^{-1})	10.8	4.1	-0.96
Microbial indicators			
E.coli (CFU 100 mL^{-1})	3393	0	**-6.87**[#]
Total coli. (CFU 100 mL^{-1})	12,272	0	**-6.87**[#]

[a] Untreated surface water samples collected in same region (Wilbers *et al.*, 2014)

n for untreated surface water is 101 for metals and Cl; 223 for other parameters

[b] piped-water quality from stations with surface water intake.

n for piped-water with surface water intake is 9 - 17 (see table 1)

[#] Significant difference between piped-water and its original source at $p < 0.05$

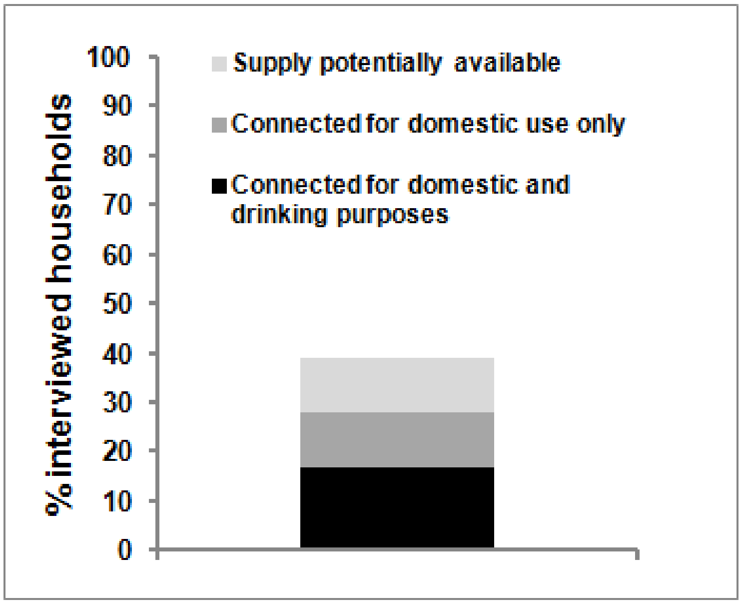


Figure 20 – Availability and connection rate to piped-water in the rural areas of the selected sites in the MD

6.4 Discussion

6.4.1 Pollution of piped-water supplies

This section discusses the potential causes of pollution of piped-water supplies and the reasons for communities to reject this water source for drinking. It should, however, be noted that the presented results are based on data collected from a selected area in the MD. Collecting piped-water samples and conducting household interviews in the entire MD was not performed due to limitations in available time and resources. Thus, piped-water quality outside the selected stations could be different than that presented in this study.

Salinity

Salinity, which is represented in this study by the concentration of Cl, was found to be unaffected by the treatment systems of water supply stations in the MD. Thus, when intake sources have high Cl concentrations this may lead to exceedance of the drinking water guideline in piped-water. Water supply stations with surface water intake did not show Cl concentrations above guideline values because: i) water supply companies do not use the saline surface waters in coastal regions and ii) inland surface waters are not affected by sea water intrusion (White, 2002). On the other hand, saline groundwater bodies in the MD can be found in both coastal and inland regions. This finding is supported by Nuber *et al.* (2005) who found Cl concentrations in groundwater ranging from 150 to 1,200 mg L^{-1} in inland provinces (two areas of Can Tho and Hau Giang). Our own groundwater samples in household wells with depths between 30 – 130 meters in the region (*Wilbers et al.*, in preparation) also show elevated Cl concentrations at various locations in Can Tho, Hau Giang and Soc Trang provinces. The occurrence of saline groundwater bodies is likely to be the reason for the high Cl concentrations in piped-water from groundwater intake that was observed in 18% of the samples. As a consequence of increasing groundwater extraction and seawater intrusion, an increasing number of water supply stations using groundwater could be threatened by high salinity levels in the near future. Reis and Mollinga (2009) reported that groundwater levels in the MD are decreasing at a rate of 0.5 – 0.7 m per year. This continuous decrease, which is mainly caused by overexploitation by supply stations, industry and domestic wells, might lead to the intrusion of more saline water from the coast into groundwater sources in the near future (Wagner *et al.*, 2012). Furthermore, predicted sea level rise is likely to lead to further salinization of ground- and surface water sources. A possible solution for water supply stations affected by saline groundwater is to increase the use of surface water sources, which are less saline, especially in the inland provinces (Can Tho and Hau Giang), due to the continuous fresh water input from the Mekong River. However, surface water may contain potentially hazardous chemicals like pesticides (Toan *et al.*, 2013; Sebesvari *et al.*, 2012) and should therefore always be monitored for these substances. In the coastal region (Soc Trang province), surface waters already contain high loads of total salts due to sea water intrusions, with concentrations between 3 and 6 g L^{-1} (Kotera *et al.*, 2008), which makes this source unsuitable for drinking. Therefore, groundwater is the main source for piped-water supplies in these regions. Moreover, suitable fresh groundwater sources in coastal areas are used intensively for irrigation purposes, e.g for rice and onion cultivation. Given this high degree of reliance on groundwater, this resource should be wisely used, especially in coastal regions, to prevent further depletion of this valuable fresh water source in the near future. Moreover, desalinization techniques to make saline waters potable may still be too expensive for this developing region. A study by Wade (2001), for example, revealed that desalinization costs by reversed osmosis are between 0.70 – 0.90 US $/m^3. In contrast, the current water price in the MD is 0.25 – 0.85 US $/m^3 (SNV, 2010), without desalinization treatments.

Nutrients

The concentrations of NO_2 and NO_3 in piped-water were low when compared to guideline values, which corresponds with the low concentrations of these nutrients in untreated water in the MD. In groundwater, reducing conditions lead to low NO_2 and NO_3 concentrations. Surface water also contains low concentrations of NO_2 and NO_3 since dissolved oxygen concentrations are low due to high water temperatures and high organic pollutant concentrations. Therefore, nitrification processes are expected to be minimal in these waters. In contrast, NH_4 was found in higher concentrations in piped-water compared with other nutrients, especially at stations in the coastal region. This could be explained by naturally high concentrations of NH_4 in groundwater at those locations which was not effectively removed during treatment. The inclusion of additional aeration techniques could further enhance nitrification processes which is likely to lead to a decrease in NH_4 levels in piped-water at those locations. Further reduction of NH_4 in drinking water is required since concentrations >0.5 mg L^{-1} could severely affect disinfection efficiency by chloride. Phosphate concentrations in piped-water were significantly lower than concentrations in its untreated sources. This is likely to be the result of the applied sand filtrations. This result is in line with Berg *et al.* (2006), who found that household sand filters in the Red River Delta in Vietnam reduced phosphate concentrations by 90%.

Metals

The concentrations of metal(loid)s did not exceed drinking water guidelines, except for Hg and Fe. The observed concentrations of Hg in piped-water were higher than the background levels in surface water and groundwater of 0.5 µg L^{-1} (WHO, 2005). The sources of Hg in piped-water could be explained by its natural presence in soils or could also be the result of external pollution by antiseptics, fungicides and other reagents containing mercury. Actual sources of Hg should be further assessed. The guideline exceedance for Fe in piped-water from groundwater sources could be caused by high natural concentrations in groundwater that were not completely removed by the treatment systems. Improved aeration techniques could further decrease Fe in piped-water supplies. Nevertheless, the quality of piped-water in the MD with respect to metals is in fact better when compared with other studies of metal contamination in piped-water sources. Berg *et al.* (2001) detected As concentrations of between 25 – 91 µg L^{-1} in water supplies after treatment in Hanoi, Vietnam, whereas As concentrations in our study reached a maximum of 8.2 µg L^{-1}. In Karachi, Pakistan, elevated concentrations of Ni and lead (Pb) exceeding WHO drinking water guidelines, were detected in piped-water supplies (Jaleel *et al.*, 2001). Ni was only found in traces in our study and Pb was not investigated. The generally low metal concentrations in our study could be explained by the common usage of sand and rock filters. Those filtering techniques sufficiently remove metals like Fe and Mn (Berg *et al.*, 2006) but might also remove other metals from water. The addition of alum to remove suspended solids from surface water in order to reduce turbidity levels and organic pollutants, could also contribute to reducing the concentration of metals in water, since many metals tend to adsorb to suspended materials. However, low metal concentrations in untreated surface- and groundwater sources could also account for the generally low concentrations in piped-water in our study sites.

Microbial pollution

The observed amounts of coliform bacteria in piped-water were significantly lower than in untreated surface water (Table 16). It is likely that the removal of bacteria was mainly achieved by the application of alum, a flocculating agent which results in the settlement of suspended matter, typically containing high loads of pathogens. Nevertheless, *E. coli* and total coliform were commonly detected in piped-water samples (for both intake sources). Possible reasons for the presence of microbial indicator bacteria in treated piped-water may include failures of treatment processes as well as contamination in the pipe system. Firstly, the chlorination process might not be optimally managed. In one case, it was observed that the chlorine tank was completely empty while piped-water was still being processed. Secondly, it was observed during the field work that some storage basins for treated water were not covered, which could lead to external pollution by air-borne dust and bird droppings. A third possible reason for microbial contamination in piped-water could be decreased chlorination efficiency due to disturbing factors such as turbidity and high concentrations of NH_4. Turbidity levels higher than 5 FTU have been reported to negatively affect the efficiency of chlorination (LeChevallier *et al.*, 1981). This threshold level was exceeded in 6% and 13% of studied piped-water samples from surface water and groundwater intake respectively. Duong *et al.* (2003) found that chlorination efficiency is negatively affected by NH_4 concentrations >0.1 mg L^{-1}. Especially in the coastal region, piped-water samples were found with NH_4 concentrations much higher than 0.1 mg L^{-1}. A fourth reason for microbial contamination in piped-water supplies could be leakage in the distribution network between the supply station and the sampling point (our samples were collected at the closest household to the supply station which was typically within 25 meters of the supply station). In general, the maintenance and adequate operating of water supply stations is still a major challenge for rural water supply stations in the MD. However this situation is not unique to the MD but also occurs in other developing regions. In South Africa for example, it was concluded that water quality from rural water supply stations did not meet water quality standards, including for pathogens, due to limited technical understanding of treatment processes by operators. As a result, coagulants and disinfectants were applied in too low or high amounts, causing water quality problems (Momba *et al.*, 2009). Possible measures to reduce microbial pollution within piped-water supplies are i) the inclusion of aeration techniques to improve nitrification processes for water sources with elevated NH_4 concentrations; ii) reduction of the interaction between treated stored water and the open air to reduce external pollution by airborne dust and bird droppings; iii) improved management of water treatment plants and education of water supply operators in order to optimally supply coagulants and chlorine to piped-water and iv) prevention and repair of leaks in the distribution system.

6.4.2 Perceptions of rural communities of piped-water quality

Although piped-water supplies are developed to provide safe and clean water to rural communities, only 43% of potentially connected households were actually using the water for drinking. Some households did not connect to piped-water at all, although there was a possible connection. Other households choose to connect, but indicated to use this water source for washing, cleaning and cooking only.

Reasons of households not to connect to piped-water

Financial reasons were found to be a main reason for the low connection rate. Household interviews showed the initial connection fee in the rural areas to be around 1,000,000 VND (ca. 45 US $ in 2013), including the costs for the pipes and the installation of the connection. Many people perceived this cost as high. In comparison, interviewed households in the rural areas reported monthly earnings of 500,000 – 5,000,000 VND. Therefore, the connection fee can be regarded as high, especially for poor households in the rural areas of the MD. Another reason for rejecting piped-water supplies is the preference for other water sources for domestic services and drinking. Some households reported having a groundwater well or harvesting rainwater for daily purposes including drinking and therefore did not require a connection to piped-water. People with a groundwater well for example, had already made major investments to gain access to this water source and this could explain why these households do not desire a connection to piped-water. Other households were found to invest in large storage basins for rainwater storage, such as large tanks, and do not, therefore, require piped-water. Preference for other potential water sources can also, therefore, be considered as a major cause for the low connection rate. These findings are in line with Reis and Mollinga (2009), who also found low connection rates to piped-water supplies due to lack of financial resources in local communities in the MD and the preference for other water sources for domestic and drinking purposes.

Reasons of households not to drink piped-water

An observed reason for rejecting piped-water supplies for drinking is the perceived poor quality of piped-water. In the MD, people judge the quality of drinking water mainly based on taste, smell and color (Özdemir *et al.*, 2011). In our study, some piped-water samples had elevated turbidity levels and Cl and Fe concentrations which affect color and taste, respectively. This may have contributed to the perception that piped-water would be unsafe and to its rejection as drinking water source and could explain the number of households that use piped-water for domestic purposes only. The reliability of supplied piped-water was another concern in some of the studied areas, which led to the fact that households used more reliable sources like groundwater and even surface water.

6.4.3 Alternative water supply facilities

In general, there are various concerns with respect to piped-water supplies. Therefore this water source cannot be regarded as the only solution for safe water supplies in the rural areas of the MD. Other measures should be considered to provide safe and clean water to rural communities in the MD, such as harvested rainwater and surface and groundwater. Harvested rainwater, for example, could be a good alternative, especially for low-income families since, when properly stored, the quality is generally good when compared with groundwater and surface water (Wilbers *et al.*, 2013). However, the quantity of this water source could be insufficient in the dry season. Therefore, Point-of-Use (POU) treatment systems should also be encouraged to generate home-made safe water supplies from groundwater and surface water sources. Household treatment systems such as sand and/or iron filters were found to effectively remove contaminants including arsenic (Berg *et al.*, 2006; Noubactep *et al.*, 2009). Another alternative is the development of decentralized water provision units (DWPU) that supply drinking water to remote communities by using the abundantly present surface- and/or groundwater sources. DWPU's can be equipped with low-tech, cheap and effective treatment measures to provide safe water to remote communities. Noubactep *et al.* (2012), for example, propose the use of zerovalent iron between two layers of sand in order to effectively remove chemicals, arsenic, nitrate and viruses. Zerovalent iron based filters are affordable, appropriate and effective and thus a decent water treatment technique for remote communities (Noubactep, 2013). Furthermore, the use of small, transportable and easy to use gravity-driven dead end membrane filtration units could be an effective way of supplying drinking water to remote communities (Frechen *et al.*, 2011). In general, the combination of the use of harvested rainwater and decentralized water treatment plants in remote areas in the MD could significantly increase the quality of drinking water for communities, and will most likely reduce the prevalence of various water-related diseases.

6.5 Conclusions and recommendations

Although piped-water is considered to be a safe and clean water source by the national government, WHO and Vietnamese drinking water guidelines are exceeded at water supply stations in the selected study sites of the Mekong Delta in Vietnam for pH, turbidity, Cl, NH_4, Fe, Hg, *E. coli* and total coliforms (among the investigated parameters in this study). Furthermore, the quality of piped-water varies depending on location and intake source. Some piped-water supply stations that use groundwater were found to exceed drinking water guidelines for Cl, although this was not observed for supply stations using surface water. Due to overexploitation of groundwater in the MD for drinking, domestic and irrigation purposes, groundwater levels continue to drop which increases saline intrusion. Therefore, piped-water stations that use groundwater have a risk of becoming unsuitable, since desalinization techniques are too expensive for this developing region. The highest NH_4 concentrations in piped-water were detected at coastal supply stations and were due to high natural concentrations of this nutrient in groundwater which were not effectively removed by current treatment processes. In contrast, piped-water with surface water intake did not exceed WHO and Vietnamese drinking water guidelines at all for NH_4. Mercury (Hg) concentrations in piped-water exceeded WHO guidelines for two out of four coastal supply stations, whereas this was only the case for one supply station in the inland provinces. Moreover, highest Hg concentrations in water were found at supply stations with groundwater intake. The reasons for elevated Hg concentrations in piped-water should be further assessed. Besides several quality issues associated with piped-water, the connectivity rate of rural communities to piped-water supply stations is also concerning. In the generally poor rural areas of the MD, many people cannot financially afford connection charges or do not switch to piped-water due to the presence of other easily accessible sources or the perceived poor quality and reliability of piped-water. Therefore, less than 50% of the rural community with a potential connection to piped-water actually uses this source for drinking.

In order to improve the quality of piped-water by further decreasing concentrations of NH_4 and metals like Fe, installation of aeration processes in supply stations is recommended. Water supply stations should also improve the management of their treatment system and prevent post-treatment pollution in order to prevent the occurrence of pathogens in piped-water supplies. It is also urgently recommended that management strategies be developed for a sustainable use of groundwater sources to maintain drinking water supplies for future generations. One such strategy in coastal areas could be the transition from crops with low salinity tolerance to agricultural systems which are more tolerant to high salinity levels in order to reduce the pressure on valuable groundwater sources. When supply stations are better maintained and are more reliable in terms of delivered quantity, the use of piped-water to communities may increase. However, in remote areas with scattered settlements, focusing on alternatives like proper rainwater harvesting techniques and decentralized (low-tech) water supply systems that can also provide safe water for these generally low-income households is recommended.

7. Comparative risk assessment for raw and household stored drinking water sources for pathogens, metal(loid)s, nutrients and salinity

Abstract

In rural areas of the Mekong Delta, most people rely on surface-, ground-, rain-, piped- and bottled water for drinking. These drinking water sources may potentially be contaminated with pathogens, metals, nutrients and salts although the rate of pollution could significantly vary between sources. A comparative risk assessment framework is used to identify which water source(s) cause the highest health-related risks based on water quality (*E. coli* and total coliforms) and people's perception towards the different drinking water sources. The result of this risk assessment show that from the five water sources used for drinking, harvested rainwater and piped-water have the highest and lowest risk index for pathogens respectively. This high risk index for harvested rainwater is caused by: i) contamination of rainwater after collection due poor storage and coverage conditions; ii) the perception that this water source is safe and clean and no disinfection is required and iii) intensive use of this water source for drinking especially in the wet season. Moreover, peak incidents of children diarrhea are observed in the early wet season when households start using rainwater for drinking. This risk needs therefore to be addressed urgently to decision makers in this region. Metals including As, Mn and Fe were also found in several (stored) drinking water sources, exceeding drinking water guidelines although nutrients and salinity did not pose a risk to human health. Educational programmes for rural communities are therefore needed to raise awareness regarding pollution status of water and the need to disinfect water even when it is perceived clean as in the case of harvested rainwater. Furthermore, storage conditions, location and behavioral aspects should also be considered to further decrease pathogen concentrations in rural drinking water supplies. In addition, sand filters are suggested to remove metal(loid)s from water.

7.1 Introduction

In many developing regions like the rural Vietnamese Mekong Delta (MD), people rely on naturally available water sources such as surface-, ground- and rainwater (Herbst *et al.*, 2009). Although the development of treated piped-water supplies is encouraged in the MD (MARD, 2012), its actual use is still below 10% for rural households in Vietnam (SNV, 2010). The reliance on (untreated) natural water sources may lead to severe health-related risks since these sources are often contaminated with various pollutants. Water-borne diseases, caused by pathogens, are widely observed in the region. Kotsila (2012) detected the occurrence of typical water-borne diseases like diarrhea, cholera, typhoid fever in the rural communities of the MD. Natural water sources like surface- and groundwater may also be contaminated with toxic metals like arsenic and manganese. Elevated arsenic levels may lead to vomiting and diarrhea by acute poisoning while chronic arsenic exposure may lead to malignant change in almost all organs, dermatological changes, cardiovascular diseases, respiratory disease, diabetes and neutropenia (Ratnaike 2003). Manganese on the other hand could cause neurotoxicity, particularly in children (Wassermann *et al.*, 2006). Buschmann *et al.* (2008) and Berg *et al.* (2007) found elevated concentrations of arsenic, manganese and other metals in water sources used for drinking in the MD which even exceeded drinking water guidelines. For nutrients, especially nitrate and nitrite lead to health-related risks. Related diseases include methemoglobinemia and effects on reproduction and development (Fan and Steinberg, 1996). Health-related risks associated with saline drinking water sources are not evident although drinking water guidelines are defined for Total Dissolved Solids and chloride (WHO, 2011). However, no studies were found regarding health effects caused by nutrient and/or saline contaminated drinking water sources in the MD. Instead, most studies related to health-related risks associated with household used drinking water sources focus on pathogens. This is mainly caused by the fact that microbial pollution of household stored drinking sources is related to various water-borne diseases and morbidity in developing regions such as the MD (Gundry *et al.*, 2004). A study from the World Health Organisation, for example, found that 8.5% of all deaths in Vietnam are caused by diarrhea (WHO, 2013b). Much research has therefore focused on the effects of various treatment techniques and improved storage conditions of stored drinking water in developing regions world-wide to reduce incidents of water-borne diseases caused by pathogens. Wrigley (2007) and Crump *et al.* (2005) for example found that alum and hypochlorite dosing to stored turbid canal water in the MD and rural western Kenya, respectively, resulted in significantly reduced numbers of pathogenic bacteria and incidents of diarrhea. The use of special high-density polyethelene plastic vessels in combination with chlorination of drinking water supplies is recommended since it likely has beneficial effects in the form of reduced infectious disease and greater productivity in developing countries (Sobsey *et al.*, 2003). Furthermore, Arnold and Colford (2007) found world-wide reduction of risks of child diarrhea when chlorination of drinking water supplies is applied while solar disinfection was found to reduce diarrhea incidents in children in Kenya (Conroy *et al.*, 1996). An investigation in rural drinking water supplies in Vietnam showed that boiling lead to a 97% reduction of total coliform concentrations (Clasen *et al.*, 2008). Hunter (2009) investigated the efficiency of various household treatment systems and found that ceramic filters most effectively remove microbes.

Other studies in Vietnam, Bangladesh and Bolivia emphasized people's hygiene perspectives and behavioral patterns to explain microbial contamination of household stored drinking water even after treatment and propose educational programmes to reduce health-related risks (Herbst *et al.*, 2009; Rufener *et al.*, 2010; Hoque *et al.*, 2006). In general, various water treatment systems, options for improved storage conditions and educational programmes are proposed to reduce incidents of water-borne disease caused by microbial contamination in household stored drinking water supplies. Besides pathogens, arsenic was found to be another factor that severely affects the safety of drinking water supplies. Hoque *et al.* (2006) found that the rate of access to safe drinking water supplies in Bangladesh was reduced significantly when arsenic was included compared with the situation in which only bacteriological quality was considered.

Severe health-related risks caused by the consumption of household stored drinking water supplies are observed in various developing regions including the MD. However, households in the MD use stored drinking water supplies from various sources with a different quality. Canal waters in the MD for example contain total coliform concentrations in the range 10^3 – 10^6 CFU 100 mL^{-1} while natural groundwater contain 10^0 – 10^3 CFU 100 mL^{-1} (Isobe *et al.*, 2004).

Groundwater and surface water have been found with elevated concentrations of heavy metals while rainwater for example showed lower metal concentrations (results presented in previous chapters). People in the MD also judge water sources on physical parameters like taste, color, safety, reliability and smell (Özdemir *et al.*, 2011), which may likely result in different handling and treatment approaches for the different water sources. Thus different health-related risks may occur between the various water sources used for drinking although this has not been investigated in detail to date in the MD. Besides household stored water, piped-water supplies in the MD were also found to be contaminated with pathogens and metals, even after treatment. An assessment and comparison of health-related risks of all drinking water sources is therefore important and may be useful for management actions to reduce incidents of water-borne diseases. The outcome of this study may also be relevant for other developing regions world-wide were naturally available water sources are also used for drinking.

The objectives of this chapter are therefore: i) to assess differences in perceptions regarding the various drinking water sources such as applied treatments prior to drinking; ii) to investigate the concentrations of microbial indicator bacteria (*E.coli* and total coliforms), heavy metals, nutrients and chloride in different raw as well as household stored drinking water sources; and iii) to identify hazards and develop 'risk indexes' of the different (household stored) drinking water sources to identify and compare the water source with the highest health-related risks, within particular for pathogens and metals, to assist decision makers in the development of drinking water management strategies for this developing region.

7.2. Materials and Methods

7.2.1 Study area

The MD is located in the south of Vietnam (Longitude 106°13’73’’E; Latitude 10°18’45’’N), has a tropical climate and is influenced by the southwestern monsoon which generates dry and wet seasons (MRC, 2005). The average annual rainfall is 1,660 mm defined by 23 years of measurements with main precipitation during wet season May – October (Delta Alliance*,* 2011). The MD was formed by accumulation of sediments from upstream areas during millions of years which resulted in four main aquifers (Holocene, Pleistocene, Pliocene and Miocene) that serves as a drinking water resource to local communities in the region (Wagner *et al.*, 2012). The MD is mainly an agricultural area and the most dominant land-use systems include rice, fruit orchards, various upland crops, fish and shrimp aquaculture, and livestock rearing (GSO, 2012b). The landscape is divided by an intensive network of natural and artificial rivers and canals which are used for various services including transportation, washing, cleaning and drinking. The total population was 17.4 million in 2012 (GSO, 2012a). In the rural areas, most of the people live along the banks of rivers and canals. Larger villages and cities on the other hand are mainly located near main rivers and intersections of main canals. Piped-water supplies are mostly available in villages and cities while people in rural areas mostly depend on local, natural water sources for daily use including drinking. All water samples were collected and all household interviews were conducted in three centralized provinces of the MD (Can Tho, Hau Giang, Soc Trang).

7.2.2 Sampling and analytical procedures

All water samples were collected between November 2011 – October 2012. A total of 248 canal surface water-, 123 well groundwater- 78 stored harvested rainwater-, 41 piped-water samples have been collected and the sampling and analytical procedures are described in previous chapters. In addition to those samples, 20 household stored surface water-, 20 household stored groundwater and 5 direct rainwater samples were collected to discriminate between microbial contamination of the water source and during its storage. For metals, 8 household stored surface water and 20 household stored groundwater samples were selected. For nutrients and chloride, 8 household stored surface water samples were selected only. No direct rainwater samples were analyzed for metals, nutrients and chloride. The household stored water samples were collected in areas close to sampling locations of untreated water sources in order to prevent spatial differences. Prior to sampling the household stored water, the house owners were asked which water source they used in their storage basin. The responses of people were checked on location (i.e. confirm the presence of a groundwater wells when people indicated to use groundwater and the intake location at the canal when people indicated to drink surface water). All sampling locations were recorded with a GPS device (Garmin ETrex, Olathe, KS, USA). The direct rainwater samples were all collected in Can Tho City. Ten bottled water samples were also selected by buying sealed bottles from different brands in local shops near Can Tho City.

Stored household water samples were collected directly from the storage basins that were used for consumption at the time of sampling to simulate the water use by local people. Rainwater samples were collected directly via the sampling bottles leaving them exposed to the open air during rainfall event. For microbial analysis, 100 mL sterilized glass bottles were used for sampling. All samples were cooled with ice and stored in the dark during transportation and delivered at the laboratory within 8 hours after sampling. Directly after arrival at the laboratory, the samples were analyzed for *E.coli* and total coliforms by pipetting 1 mL of sample water on 3M^{TM} petrifilm^{TM} coliforms count plates (3M, St. Paul, MN, USA). *E.coli* and other coliforms colonies were counted 24±4 hours after incubation at 37ºC. The analysis procedure was duplicated (n=2) to achieve more accurate counts of microbial colonies. For metals, 50 mL PE bottles were uses. Samples were acidified by nitric acid (Merck Millipore, Billerica, MA, USA). Acidified samples for metal analysis were stored in a fridge at 5°C and analyzed within six months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA). For nutrients and chloride, 100 mL PE bottles were used. All samples were stored at 5 °C, pre-treated by syringe filters (0.45 µm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 hours of collection. NO_3, NO_2 and Cl were measured using Spectroquant ® cell tests (Merck Millipore, Billerica, MA, USA) by applying the following ranges: NO_3-N: 0.5 – 18.0 mg L^{-1}; NO_2-N 0.002 – 1.00 mg L^{-1} and Cl^- 2.5 – 250 mg L^{-1}.

7.2.3 Household interviews

A total of 542 household interviews were conducted in the MD in order to assess the water sources used for drinking and to which extent those sources are used between seasons. Also perceptions towards different drinking water sources were assessed by defining the rate of treatments applied for each of the indicated drinking water sources. More information regarding the structure of the household interviews can be found in chapter 1.

7.2.4 statistical analysis and computation

Statistical analysis was carried out with SPSS version 20.0. The concentrations of selected pollutants in the different (stored) drinking water sources were statistically compared with each other by the non-parametric Mann-Whitney Test. This test was selected because the data were not normally distributed, even after log-transformation, and was unequal in size.

Health risks associated with pollutant concentrations in drinking water sources are defined based on a comparative risk assessment framework such as those mentioned by a review of Briggs (2008) to integrated environmental health impact assessment frameworks (*Fig. 21 – Integrated environmental health impact assessment in relation to other forms of risk and impact assessment, Briggs, 2008*). This framework includes elements such as the identification of hazards and it sources, the exposure to- and the identification of risks (risk assessment) while considering population characteristics and behavior, rates of diseases and health impacts and perceptions (comparative risk assessment) (Briggs, 2008). Health-related risks associated with drinking water sources for pathogens are in this study defined by the microbial contamination rate of the drinking water sources (hazard), multiplied with the percentage of households that indicated not to apply disinfection due to good perceived quality of the drinking water sources (exposure) and is shown in equation 1. The microbial contamination of drinking water sources is represented by the presence of *E. coli* and total coliforms since these bacteria are widely accepted as good indicator bacteria for various pathogens and are therefore included in many drinking water regulations (Edberg *et al.*, 2000). Health-related risks associated with selected metals (As, Ba, Fe and Mn) in drinking water sources are defined by the concentrations in the drinking water sources regardless of disinfection (equation 1).

$$R_{dws} = H_{dws} * f_{nd.dws} \qquad (1)$$

Where:

R_{dws}: health-related risk of a certain drinking water source

H_{dws}: hazard of a certain (household stored) drinking water source defined by the pollution rate of the investigated water samples of the drinking water source (see equation 2)

$f_{nd.dws}$: the fraction of households that does not disinfect the drinking water source prior to consumption (boiling). Alum treatment is not considered as a disinfection technique in this study. For metals, the $f_{nd.dws}$ is set as a fixed value of 1 since disinfection is assumed not to affect the concentrations of these water quality parameters.

The purpose of this risk assessment equation is to compare health-related risks of different drinking water sources with each other to investigate which source(s) are best of drinking or not based on current quality and perceptions. In addition, the use of drinking water sources is also investigated to evaluate the actual risk in the selected region. This may be of interest to local decision makers and provides an important part of the information needed to support risk management (Covello and Merkhofer, 1993). The hazard of a drinking water source (H_{dws}) is defined on the concentration range of pollutants in the water. Thus, a water source with higher pollutant concentrations leads to a higher hazard. To define a hazard score for pathogens for a certain drinking water source, the classification scheme for thermotolerant (feacal) coliforms or *E. coli* in water supplies set by the World Health Organisation is used (WHO, 1997) while for metals the contamination classes were developed based on WHO drinking water guidelines (2011), which are presented in Table 17. For total coliform hazards of drinking water sources, the same classification scheme as used for *E. coli* is used although the scheme is not specifically focused on total coliforms due to limited sanitary relevance (WHO, 1997). Nevertheless, total coliforms are considered in this study due to generally higher concentrations in water sources compared to *E. coli* which supports the interpretation of comparison of microbial pollution between water sources.

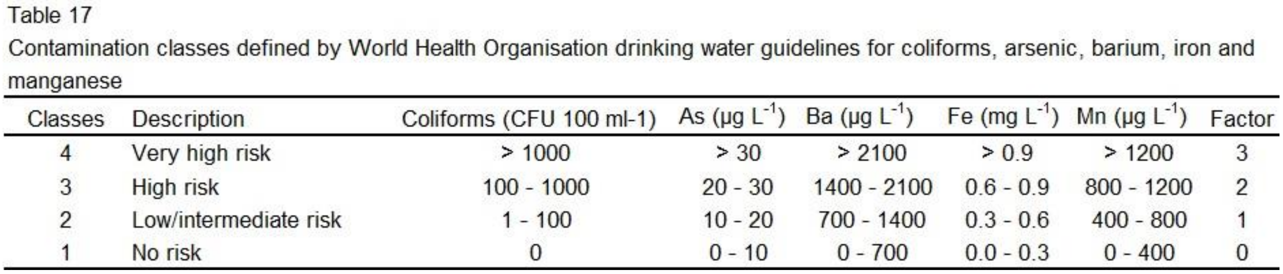


Table 17

Contamination classes defined by World Health Organisation drinking water guidelines for coliforms, arsenic, barium, iron and manganese

Classes	Description	Coliforms (CFU 100 ml-1)	As (µg L^{-1})	Ba (µg L^{-1})	Fe (mg L^{-1})	Mn (µg L^{-1})	Factor
4	Very high risk	> 1000	> 30	> 2100	> 0.9	> 1200	3
3	High risk	100 - 1000	20 - 30	1400 - 2100	0.6 - 0.9	800 - 1200	2
2	Low/intermediate risk	1 - 100	10 - 20	700 - 1400	0.3 - 0.6	400 - 800	1
1	No risk	0	0 - 10	0 - 700	0.0 - 0.3	0 - 400	0

Based on the contamination rate and the identified factor scores corresponding to the pollution classes, hazard scores for drinking water sources are calculated via equation 2.

$$H_{dws} = \Sigma\left[\%dws_{n(1-4)} * factor_{n(1-4)}\right] \quad (2)$$

Where:

$\%dws_{n(1\text{-}4)}$: percentage of samples of a certain drinking water source within classes 1 – 4

$Factor_{(n1\text{-}4)}$: factor score corresponding to the risk classes 1 – 4

Based on this equation, the minimum hazard score of a certain drinking water source is 0 (100% of samples of a drinking water source within class 1) while the maximum hazard score is 300 (100% of samples of a drinking water source within class 4). Risks associated with nutrients and salinity are described textually without formulating hazard and risk scores.

7.3 Results and discussion

7.3.1 Applied household water treatments and perceptions

Household level water treatment is applied when people perceive water as unsafe for direct consumption. Pre-treatment with chemicals like alum are used in an attempt to remove pollutants from water like suspended solids or when water has an unfavorable smell, color and/or taste. Depending on the water source perception, people also indicated to disinfect water prior to use and boiling was the most frequently mentioned disinfection technique. The rate of alum treatment and disinfection of the different drinking water sources is presented in Table 18.

Although rural communities in the MD always use alum to treat surface water sources, further disinfection is not systematically applied. This could be explained by the fact that alum treated surface water looks clear, has no smell and no visible pollutants. Thus, some households may perceive this water source as safe for drinking. However, all collected household stored surface water samples were still contaminated with *E. coli* and/or total coliforms after alum treatment which may result in health concerns if disinfection is not applied prior to drinking. A similar pattern is observed when groundwater is used, although alum is less intensively applied for this source of water. Households indicated to use alum treatment for groundwater supplies only when the water has a metallic (iron) smell. A study to groundwater quality in Can Tho, Hau Giang and Soc

Trang provinces showed that 70% of the 116 untreated groundwater samples contained Fe concentrations above the drinking water guideline of 0.3 mg L^{-1}, which is the defined threshold level for unfavorable smell (Chapter 5). This percentage is in line with the observed percentage of households that are not using alum (61%) and could confirm the relationship between Fe concentrations in groundwater and applied alum treatment. Moreover, 27% of households drinking groundwater, indicated not to disinfect water due to positively perceived water quality. Nevertheless, collected stored groundwater supplies were also contaminated with *E. coli* and/or total coliforms and could result in health impacts when disinfection is not applied. Harvested rainwater is only treated by alum on occasion while disinfection is only applied by less than 50% of households using rainwater for drinking. Only one household using rainwater for drinking, indicated to use both alum and disinfection prior to drinking. This finding is in line with the observation that rainwater is perceived as a high quality drinking water source due to positively judged physical parameters (Özdemir *et al.*, 2011; Herbst *et al.*, 2009). Also Lye (2002) found that a majority of rainwater consumers world-wide do not apply any treatment techniques before ingestion. However, 34% of stored rainwater samples were contaminated with *E. coli* while 94% of those samples were contaminated by total coliform bacteria. Thus, people may be exposed to pathogens when stored rainwater is not disinfection prior to consumption. In contrast, most of the people using piped-water, apply disinfection techniques prior to drinking. Piped-water usually has no color or smell which could explain that people do not intensively use alum. However, this water source is clearly not trusted as a safe drinking water source although people are aware this water is treated in the supply station. In fact, 7% of the piped-water samples were contaminated with *E. coli* while 51% of the piped-water water samples were contaminated by total coliforms and the precautious disinfection that household apply is therefore necessary.

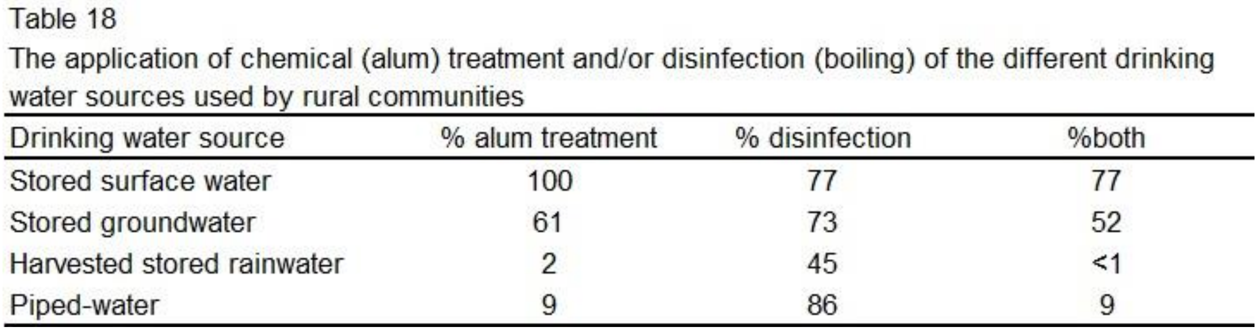


Table 18

The application of chemical (alum) treatment and/or disinfection (boiling) of the different drinking water sources used by rural communities

Drinking water source	% alum treatment	% disinfection	%both
Stored surface water	100	77	77
Stored groundwater	61	73	52
Harvested stored rainwater	2	45	<1
Piped-water	9	86	9

7.3.2 Water quality

This section describes the water quality of raw and household stored water sources for selected pathogens and metals.

Pathogens

E. coli and/or total coliform bacteria were detected in all investigated (raw and household stored) drinking water sources, except for raw rainwater. However, large differences in concentrations were found between the different raw water sources and storage conditions (Fig. 21).

In general, median coliform concentrations in stored water are in a similar range (10^3 – 10^4 CFU 100 mL^{-1} for total coliforms) regardless of the water source. These concentration levels exceed WHO drinking water quality guidelines which suggests the absence of *E. coli* and other coliform bacteria in drinking water supplies (WHO, 2011). *E. coli* and total coliform concentrations in canal and river water (SW source) are however significantly higher than household stored surface water supplies (z-value -4.47; $p<0.001$). Natural surface waters in the MD are highly contaminated with sewage water and animal waste which results in high concentrations of pathogens. Isobe *et al.* (2004) who also investigated surface water at various locations in the MD reported similar results. Inhabitants of the MD are aware of this pollution problem and always treat surface water before use. The applied treatment is usually a combination of flocculation (mainly with alum) and boiling. The application of alum, that causes the flocculation and subsequent settlement of microbe rich suspended sediments, is likely the reason for the lower concentrations of *E. coli* and total coliforms in stored surface water compared with natural canal and river water. This finding is in line with Wrigley (2007) and Crump *et al.* (2005) who also found reduced concentrations of microbial pollutants due to alum treatment in turbid surface waters. An opposite pattern is however visible for groundwater where significantly higher coliforms concentrations were found in stored water compared with its original source (z-value -7.42; $p<0.001$). Natural groundwater often contains low concentrations of pathogens since the soil column serves as a natural filter for surface borne contaminations. Also the concentrations of pathogens in stored rainwater are higher compared to rainwater collected directly during rainfall events (z-value -3.41; $p=0.001$). This finding is in line with Wright *et al.* (2004) who found that the decline in water quality between source and point-of-use in terms of (total) coliforms is proportionally greater when source water is largely uncontaminated, which is generally the case for groundwater and rainwater sources. This decline in water quality may be explained by a few causes. Firstly, water may already be contaminated during the collection of water via i.e. roofs and gutter system (rainwater), and via dirty plastic tubes and malfunctioning pumps to transport surface and/or groundwater to storage basins. Secondly, when storage basins are not covered (which is usually the case in the MD) most people collect water from the top of the basin which results in hands and cups being dipped in the water. Moreover, hygienic perceptions such as the need of washing of hands after sanitary use to prevent spreading of microbial contamination are not widely known (Herbst *et al.*, 2009). Thus when people collect water from their storage basin after sanitary use, this further increases the risk of microbial pollution of stored drinking water sources. Uncovered water sources also enhance the possibility of pollution by air-borne dust, leaves and even direct bird droppings. Thirdly, many households use chemicals like alum aiming to improve the quality of groundwater. When chemicals are added by hand, which is a common practice; microbial pollutants can easily be introduced in the storage system. In general, the combination of similar handling processes, collection, storage and behavioral patterns with respect to stored water, could explain the low variation in microbial quality between stored water supplies. This finding is in line with Clasen and Bastable (2003) who concluded that stored drinking water supplies in developing regions are contaminated most severely at the point of use.

Harvested stored rainwater on the other hand, showed slightly but nevertheless statistically significantly lower concentrations of *E. coli* and total coliforms compared to stored surface- and groundwater (z-value: -3.27; $p=0.001$) and shows larger variability in observed pathogen concentrations. All rainwater samples were however collected in the rainy season only. Thus, when harvested rainwater was sampled directly after an intensive rainfall event, pathogen concentrations are most probably lower due to strong dilution of pollutants and low influence of storage duration.

Even in households connected to piped-water supplies, coliform bacteria were detected. The causes of contaminated piped-water could be failures in treatment processes, improper coverage of treated piped-water supplies or contamination during transport e.g. via leaks (Chapter 6). However, the microbial quality of stored piped-water is not subject of this study since most households use this water source directly from a household tap without storage.

The microbial quality of bottled water was also assessed in the frame of a small size screening study. No *E. coli* and total coliform bacteria were detected. However, there are many regional enterprises producing bottled water from various sources in the Mekong Delta, thus a detailed investigation of bottled water quality is required before reliable conclusions can be drawn for this specific water source.

Selected metal(loid)s

For metal(loid)s, As, Ba, Mn and Fe were selected for analysis since concentrations of these metal(loid)s were found above WHO drinking water standards for multiple water sources. The concentrations of these metals in the different (household stored) water sources are presented in Fig. 22.

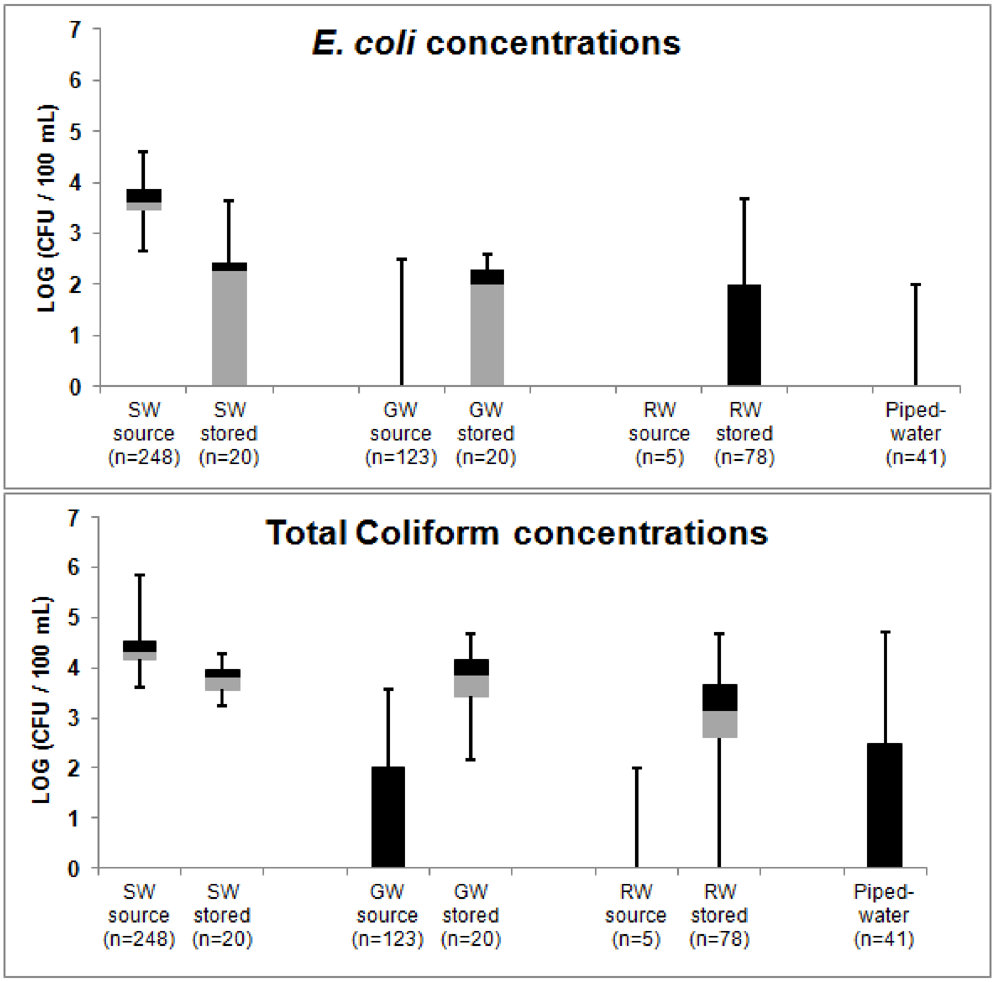


Figure 21 – Concentrations of *E. coli* and total coliforms in different drinking water sources (raw and stored) used in Can Tho, Hau Giang and Soc Trang provinces of the MD. Results are presented as boxplots and show maximum (top of the line) – 75 percentile (top of black bar) – median (boundary between black and grey bar) – 25 percentile (bottom of grey bar) – minimum (bottom of the line) observed log transformed concentrations. Bottled water is not included due to lack of sufficient number of bottled water samples as number of samples were insufficient for this breakdown.
SW source: surface water from canals and rivers; SW stored: household stored surface water
GW source: raw groundwater from household wells; GW stored: household stored groundwater
RW source: direct rainwater; RW stored: household harvested rainwater

From all drinking water sources, the highest As concentrations were found in surface- and groundwater sources although most of the samples showed concentrations below the WHO drinking water guideline of 10 µg L^{-1}. Remarkably, no significant differences were observed between raw and stored surface water (z-value: -1.00; p=0.32) and raw and stored groundwater (z-value: -0.58; p=0.56) which suggests that alum treatment is not an effective manner to reduce As in drinking water supplies. Also Hering *et al.* (1997) concluded that As (III) could not be removed by coagulation with alum. This indicates that As contaminated surface- and/or groundwater sources may lead to health-related concerns when consumed for drinking whether alum treatment is applied or not. The lowest As concentrations in this study were found in household stored rainwater and in piped-water supplies.

The highest concentrations of Ba were found in groundwater. In comparison, all other water sources contained Ba concentrations below drinking water guidelines. No significant differences in Ba concentrations were found between raw and stored groundwater (z-value: -0.04; p=0.97) which suggests that alum treatment is also not a sufficient manner to reduce this metal from water as is the case for As.

In contrast, Fe and Mn concentrations were significantly lower in stored surface- and groundwater when compared to its untreated sources (Fe: p=0.000; Mn: p=0.001). This suggests that alum treatment is a sufficient technique to remove these metals from drinking water supplies. Fatoki and Ogunfowokan (2002) found that metals including Mn were effectively removed by $Al^2(SO_4)^3$ coagulant from raw water supplies. In addition, the strong differences in Mn and Fe concentrations between raw and stored surface water could also be explained by the settlement of suspended materials due to alum addition since metals tend to adsorb strongly on suspended solids. Besides the influence of alum treatment on metal reduction, increased oxygen content in stored water could also explain differences between raw and stored water sources. Raw surface- and groundwater often have oxygen concentrations between 0.0 – 3.0 mg L^{-1} (chapter 4 and 5) which causes mobilization of these metals in the water phase. However, household stored drinking water supplies (i.e. jars) contain oxygen concentrations between 5.0 – 10.0 mg L^{-1} (own unpublished data). These higher oxygen concentrations in stored water supplies lead to the oxidation of Fe and Mn compounds which results in insoluble Fe and Mn oxides that precipitate on the bottom of storage basins (Land, 1999). This is confirmed by the observation that drinking water storage basins often contain a grey – redbrown layer of settled materials. In general, the lowest concentrations of As, Ba, Fe and Mn were found in household harvested rainwater and could be explained that natural rainwater contains low metal concentrations. However, in household harvested rainwater elevated concentrations of lead (Pb) and zinc (Zn) were found (not presented in Fig. 22, more information in chapter 3). Piped-water, which origin is raw surface- and/or groundwater, contains lower metal concentrations compared to untreated sources. This suggests that the treatment techniques work effectively to reduce metals from raw water sources (more information in chapter 6).

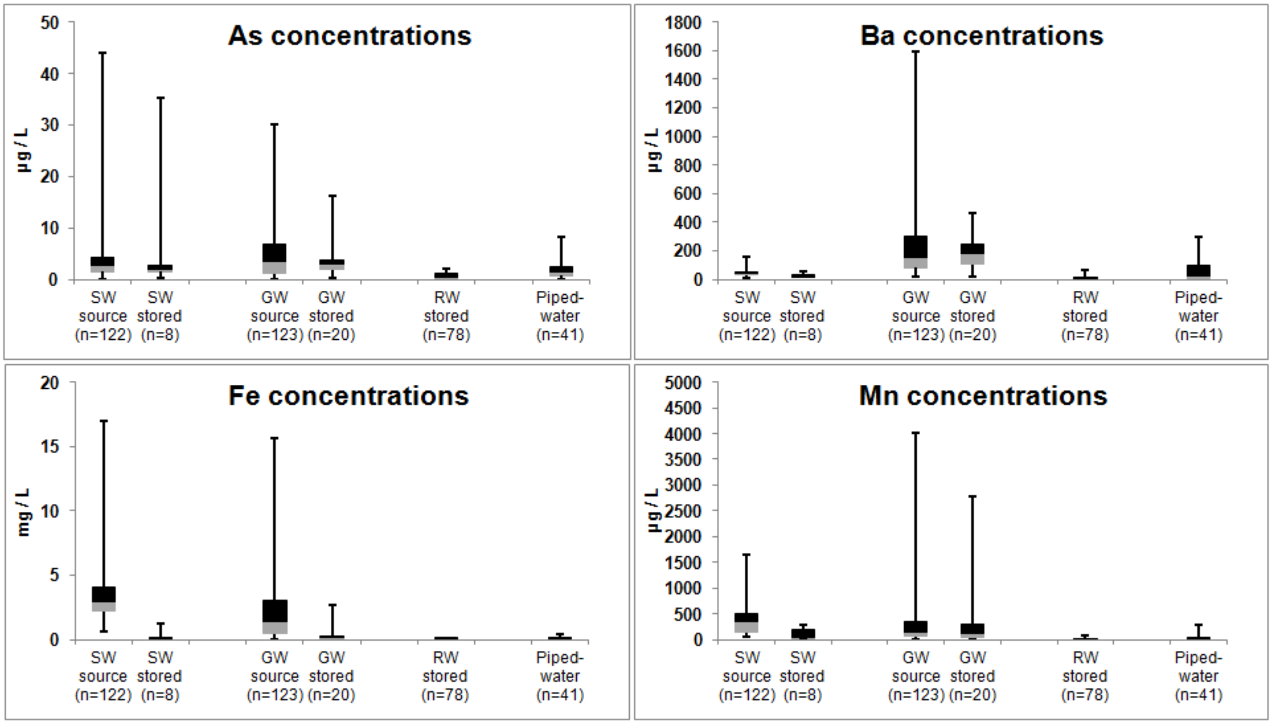


Figure 22 – Concentrations of arsenic (As), barium (Ba), iron (Fe) and manganese (Mn) in different drinking water sources (raw and stored) used in the Can Tho, Hau Giang and Soc Trang provinces of the MD. Bottled water is not included.
Results are presented as boxplots and show maximum (top of the line) – 75 percentile (top of black bar) – median (boundary between black and grey bar) – 25 percentile (bottom of grey bar) – minimum (bottom of the line) observed log transformed concentrations.

SW source: surface water from canals and rivers; SW stored: household stored surface water
GW source: raw groundwater from household wells; GW stored: household stored groundwater
RW source: direct rainwater; RW stored: household harvested rainwater

7.3.3 Hazards and risk-index for pathogens and metal(loid)s in drinking water sources

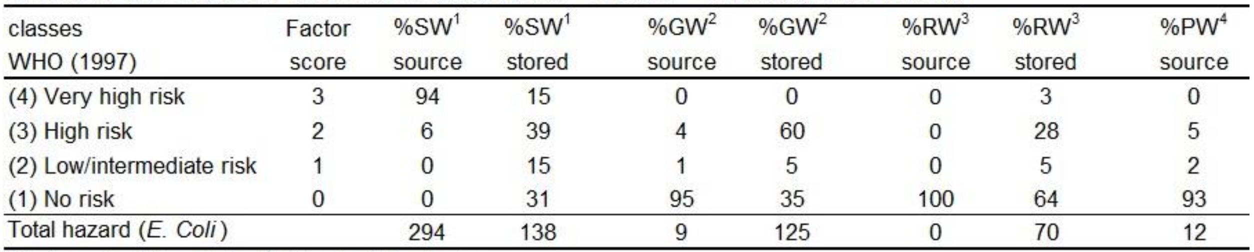
This section describes the calculated hazard scores and risk index for raw and household stored water sources for the selected pathogens and metal(loid)s.

Pathogen hazards

The various drinking water sources show different health-related hazards due to fluctuations in water quality. These hazards for (stored) surface-, ground- and rainwater and tapped piped-water supplies are presented and compared for *E. coli* and total coliforms in table 19a,b.

Table 19a

E. Coli hazards of (stored) water sources (Total hazard = Σ [factor * % drinking water source])

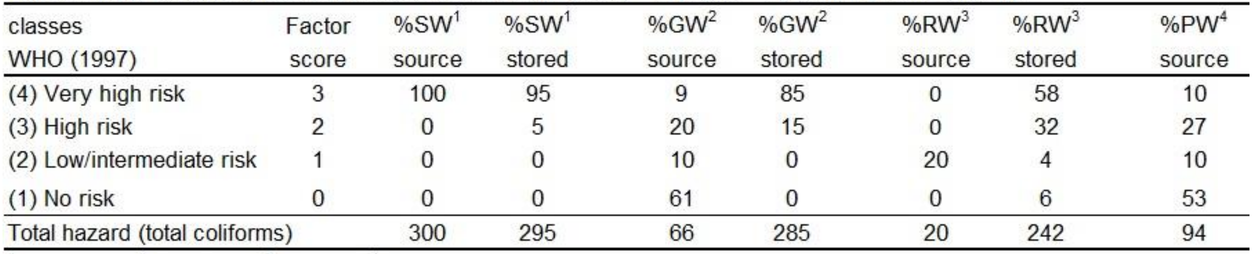


classes WHO (1997)	Factor score	%SW[1] source	%SW[1] stored	%GW[2] source	%GW[2] stored	%RW[3] source	%RW[3] stored	%PW[4] source
(4) Very high risk	3	94	15	0	0	0	3	0
(3) High risk	2	6	39	4	60	0	28	5
(2) Low/intermediate risk	1	0	15	1	5	0	5	2
(1) No risk	0	0	31	95	35	100	64	93
Total hazard (*E. Coli*)		294	138	9	125	0	70	12

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Table 19b

Total coliform hazards of (stored) water sources (Total hazard = Σ [factor * % drinking water source])



classes WHO (1997)	Factor score	%SW[1] source	%SW[1] stored	%GW[2] source	%GW[2] stored	%RW[3] source	%RW[3] stored	%PW[4] source
(4) Very high risk	3	100	95	9	85	0	58	10
(3) High risk	2	0	5	20	15	0	32	27
(2) Low/intermediate risk	1	0	0	10	0	20	4	10
(1) No risk	0	0	0	61	0	0	6	53
Total hazard (total coliforms)		300	295	66	285	20	242	94

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Untreated as well as household stored surface water show the highest total hazard values since most water samples of these drinking water sources were contaminated with *E. coli* and total coliforms at high concentrations (*E. coli* > 10^2- and total coliforms > 10^3 CFU 100 mL^{-1}). Untreated surface water has the maximum hazard score for total coliforms of 300, which is just slightly higher than for stored surface water. However, total coliform concentrations in untreated surface water are a factor of 10 – 100 higher compared to stored surface water. This is nevertheless not clearly visible in the total hazard value since the maximum risk class (very high risk) is defined for water with total coliform concentrations of >10^3 CFU 100 mL^{-1}, which is the case for both untreated and most stored surface water samples. Furthermore, household stored groundwater show a high total hazard value for both *E. coli* and total coliforms which is close to household stored surface water. The total hazard value with respect to stored harvested rainwater is lower for both *E. coli* and total coliforms, although almost all samples were contaminated with these bacteria. However, this is explained by the fact that in many harvested rainwater samples pathogen concentrations were lower compared to stored surface- and groundwater. Piped-water supplies show an even lower total hazard score compared to stored surface-, ground- and harvested rainwater. However, the total hazard score of piped-water is higher compared to raw ground- and rainwater.

Pathogen risk index

The risk index for each of the drinking water sources, calculated as a function of the total hazard values (Table 19a,b) and the fraction of the households not disinfecting water prior to drinking, which is presented in Table 18 are shown in Fig. 23. Risk indexes are developed for stored surface water, stored groundwater, stored harvested rainwater and piped-water since this are the pathways of exposure of microbiologically contaminated drinking water. Bottled water is not included due to lack of data.

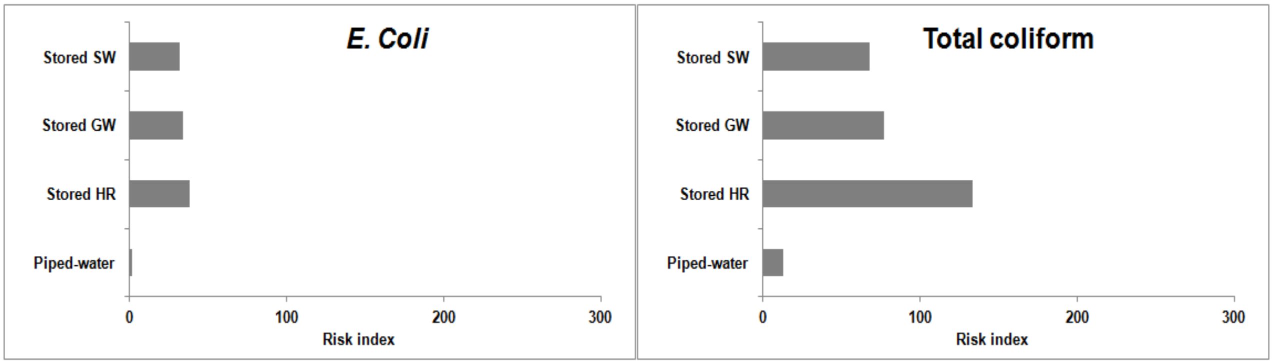


Figure 23 – A comparison of health-related risks (indicated by *E. coli* and total coliform) between drinking water sources used in the Mekong Delta based on the microbiological quality of the source and household applied disinfection treatment at point of use

The highest risk index has been calculated for household stored harvested rainwater. Thus, the highest risks of water-borne diseases with respect to drinking water sources are associated by rainwater consumption in the MD, which is, in principle, counter-intuitive, but which is explained by people´s perception (good quality water) and the resulting lack of disinfection. Moreover, rainwater is indicated as the most used drinking water source in the wet season which could indicate that many people may be affected by water-borne diseases in this season due to the consumption of contaminated rainwater. On the contrary, in the dry season the use of rainwater for drinking decreases significantly and people start using other water sources (i.e. groundwater, surface water) which they usually disinfect due to lower perceived quality. As a result, health-related risks associated with drinking water sources may be lower in the dry season compared to the wet season.

Data regarding children diarrhea incidents of a hospital in Can Tho for 2009 – 2011, clearly shows a peak of children diarrhea incidents in the early wet season (May – June) while lower incidents were reported in the dry season for (Kotsila, P., 2014. Personal communication, Center for Development Studies (ZEF), University of Bonn). This might suggest a relationship between the increasing consumption of untreated rainwater in the wet season and incidents of acute diarrhea. Moreover, Lye (2002) also found relationships between the consumption of untreated harvested rainwater with a variety of diseases including diarrhea and pneumonia. However, reported incidents of acute diarrhea in the early wet season could also have other causes like increasing cases of food poisoning due to high temperatures and humidity in this period (Kotsila, P., 2014. Personal communication, Center for Development Studies (ZEF), University of Bonn).

The calculated risk indices for stored surface- and groundwater are lower compared with harvested rainwater since most people disinfect these water sources. Nevertheless, there is still a considerable share of people (around 25%) drinking surface- and groundwater which only apply alum treatment but do not disinfect in addition. This group is most probably also exposed to pathogens since alum treatment alone is not sufficient to significantly reduce the concentration of pathogens. On the other hand, piped-water supplies do show a low risk index due to generally low *E. coli* and total coliform concentrations in this water source in combination with high share of population applying disinfection.

Although the application of disinfection techniques is recognized to reduce pathogen concentrations in water, it does not remove the risks completely. Boiling was found to remove 97% of thermotolerant coliforms (Clasen *et al.*, 2008) while chlorination was found to remove around 95% of pathogens in stored water (Wrigley, 2007). Moreover, water can be re-contaminated after disinfection when handled improperly. Thus, the actual risk could be higher for each household. The risk index as presented in this study is therefore only meaningful to compare water sources and water storage and handling strategies in general.

Table 20a

Arsenic hazards of (stored) water sources defined by the contamination rate of water source and the factor score based on the WHO (1996) drinking water guidelines (Total hazard = Σ [factor score * % drinking water source])

classes	Factor	%SW[1]	%SW[1]	%GW[2]	%GW[2]	%RW[3]	%PW[4]
WHO (1997)	score	source	stored	source	stored	stored	source
(4) Very high risk	3	10	12	1	0	0	0
(3) High risk	2	0	0	2	0	0	0
(2) Low/intermediate risk	1	1	0	7	10	0	0
(1) No risk	0	89	88	90	90	100	100
Total hazard		31	36	14	10	0	0

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Table 20b

Barium hazards of (stored) water sources defined by the contamination rate of water source and the factor score based on the WHO (1996) drinking water guidelines (Total hazard = Σ [factor score * % drinking water source])

classes	Factor	%SW[1]	%SW[1]	%GW[2]	%GW[2]	%RW[3]	%PW[4]
WHO (1997)	score	source	stored	source	stored	stored	source
(4) Very high risk	3	0	0	0	0	0	0
(3) High risk	2	0	0	1	0	0	0
(2) Low/intermediate risk	1	0	0	6	0	0	0
(1) No risk	0	100	100	93	100	100	100
Total hazard		0	0	8	0	0	0

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Table 20c

Iron hazards of (stored) water sources defined by the contamination rate of water source and the factor score based on the WHO (1996) drinking water guidelines (Total hazard = Σ [factor score * % drinking water source])

classes	Factor	%SW[1]	%SW[1]	%GW[2]	%GW[2]	%RW[3]	%PW[4]
WHO (1997)	score	source	stored	source	stored	stored	source
(4) Very high risk	3	98	12	61	10	0	0
(3) High risk	2	2	0	9	5	0	0
(2) Low/intermediate risk	1	0	0	11	10	0	5
(1) No risk	0	0	88	19	75	100	95
Total hazard		296	36	212	50	0	5

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Table 20d

Manganese hazards of (stored) water sources defined by the contamination rate of water source and the factor score based on the WHO (1996) drinking water guidelines (Total hazard = Σ [factor score * % drinking water source])

classes	Factor	%SW[1]	%SW[1]	%GW[2]	%GW[2]	%RW[3]	%PW[4]
WHO (1997)	score	source	stored	source	stored	stored	source
(4) Very high risk	3	2	0	5	0	0	0
(3) High risk	2	4	0	3	10	0	0
(2) Low/intermediate risk	1	34	0	13	5	0	0
(1) No risk	0	60	100	79	85	100	100
Total hazard		48	0	34	25	0	0

[1] Surface water; [2] Groundwater; [3]: Rainwater; [4] Piped-water

Metal(loid)s hazards and risk index

The health-related hazards of As, Ba, Fe and Mn differ between sources and storage conditions. The hazards for each raw and household stored water sources for the selected metals are presented in table 20a, b, c and d.

Health-related hazards are mainly observed for (stored) surface- and groundwater (As and Mn) while harvested rainwater and piped-water show no or only a low hazard score. The hazard scores for As, Ba and Mn in household stored conditions (SW stored, GW stored, RW stored, PW source) directly indicate the health-related risks. Thus the hazard score is equal to the risk index. This is explained by the fact that: i) alum treatment was performed prior to sampling in household stored water, ii) additional treatment techniques to remove metals are generally not applied and iii) disinfection techniques like boiling do most likely not reduce metal concentration. Instead, boiling of water might even lead to a slight increase in metal concentration in drinking water due to evaporation of water. The hazard score with respect to Fe does not imply a direct health risk but instead indicates whether water is suitable for drinking with respect to taste, color and odor.

In general, the hazard scores of metals are significantly lower compared to those of total coliforms. A similar result was found in a study on rural drinking water supplies in Bangladesh where the rate of access to safe water was reduced by 10%, due to As contamination, when compared with the situation in which only bacteriological contamination was considered (Hoque *et al.*, 2006). However, the hazard tables for selected metals show that health-related concerns could occur as a result of consuming drinking water in the MD. This issue needs serious attention and additional treatment techniques are recommended to further decrease metal concentrations in drinking water supplies used by rural communities in the MD.

Other investigated metals (not presented) like cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn) and magnesium (Mg) are only present in traces in drinking water sources and/or are not a threat to human health at the observed concentrations. Therefore, it is not expected that these elements will cause health-risks associated with drinking water in the MD. In contrast, mercury (Hg) was found in raw surface water at a few locations near fish farms and industrial agglomerations as well as in some piped-water samples (chapter 4 and 6 respectively).

7.3.4 Water quality and health-related risks for nutrients

For nutrients, NO_2 (0.2 mg L^{-1}) and NO_3 (50 mg L^{-1}) have defined health-related drinking water standards set by the World Health Organisation (WHO, 2011). None of the water samples collected in this study exceeded the NO_3 guidelines. In household stored surface water the maximum NO_3 concentrations were 3.2 mg L^{-1} while NO_2 was below detection limit. All household stored rainwater contained low nutrient concentrations below guideline levels while in groundwater and piped-water, NO_2 and NO_3 were not present or only in low concentrations. However, NO_2 concentrations exceeded drinking water guidelines for some raw surface water samples (chapter 4) with maximum concentrations of 0.30 mg L^{-1}. However, during storage in jars the concentrations decline rapidly most probably due to higher oxygen concentrations in stored water compared to raw surface water. In general, nitrate and nitrite do not cause health-related risks in drinking water sources in the MD. The concentrations of NH_4 and SO_4 in water were higher and even exceeded secondary drinking water guidelines set by the World Health Organisation (WHO, 2011) for some water sources. However, these nutrients do not pose a direct health-risk but only affect disinfection efficiency and physical conditions of drinking water.

7.3.5 Water quality and health-related risks for salinity

Salinity, which is represented by chloride (Cl) does severely affect the suitability of water sources for drinking by i.e. saline intrusion in canals and groundwater bodies (Chapters 4 and 5 respectively). However, in 8 household stored surface water samples where Cl was measured, the maximum concentration was 18 mg L^{-1} which is far below the secondary drinking water guideline of 250 mg L^{-1}. Cl is not expected to cause health concerns associated with drinking water sources since people do not drink water with a saline taste. For example, in Soc Trang province, none of the interviewed households indicated to use surface water for drinking and/or domestic services due to strong saline taste of water although this water source was widely available. However, high saline water could be a risk for water availability and for irrigation purposes.

7.4 Conclusions

Rural communities in the MD use several water sources for drinking which were found to be contaminated with *E. coli* and total coliforms and metal(loid)s at concentrations exceeding World Health Organisation drinking water guidelines (except for bottled water which was not intensively monitored in this study). Households do treat water before consumption although the amount and type of treatments depends strongly on the perception of the water quality sources and individual hygiene preferences. Thus, water sources such as harvested rainwater that look safe and good for drinking judged by color, odor, taste etc. are rarely treated prior to consumption. As a result, harvested rainwater shows the highest risk index for pathogens. Moreover, rainwater is the most indicated drinking water source in the wet season which shows that many people are exposed to microbiologically contaminated drinking water in this season. This could explain the peak in occurrence of children diarrhea in the early wet season in the region. There is therefore a need to develop educational programmes in the MD to inform households about the health-related risks of consuming non-disinfected stored water sources, in particular for harvested rainwater. The focus of the educational programmes should be to disinfect water, even when it is perceived as a clean and safe source with respect to color, smell, taste and odor. Authorities could also more intensively supply disinfectants to rural communities. Furthermore, storage conditions such as permanent coverage and inclusion of taps on storage basins should be encouraged to decrease the concentrations of pathogens in drinking water sources. Rural communities could also be informed about hygienic perspectives such as hand washing after sanitation which could further reduce health-related risks associated with drinking water sources. For metals, As and Mn drinking water guidelines were exceeded for household stored surface- and groundwater sources. Alum treatment does not effectively remove As from water while disinfection by boiling could even increase metal concentration in drinking water sources. Thus, additional treatment steps like sand filtration is required to further decrease risks associated with metals in drinking water. The concentrations of nutrients and Cl in drinking water sources do not cause health-related problems.

8. General conclusions and recommendations

This chapter summarizes the findings regarding the use of different water sources for drinking and domestic purposes by rural communities in the MD, their current pollution status and highlights the most important links to (possible) health-related risks. Furthermore, it provides recommendations regarding the best drinking and domestic water sources for these communities.

8.1 Conclusions

A total of five different water sources are used by rural communities in the MD for drinking, washing, cleaning and cooking. Health-risks associated with the use of these water sources depend on many factors but it is mainly influenced by the quality and availability of the water sources and people’s perceptions towards these water sources. Perception and recognition of water quality problems is acknowledged here as a pre-requisite of action (e.g. use of alternative source, application of treatment methods).

As shown in the study, each of the water sources has its own, specific quality issues, they are not similarly available to rural communities and are perceived differently by different households. Thus, the various water sources have specific influences on the prevalence of water-related diseases in the region. In addition, some water sources are not used sustainably, affecting their availability for future generations. A multi-criteria analysis (MCA) was carried out for each of the water sources based on water quality, availability, perceptions and sustainable use of these water sources (defined by personal observations and extensive literature review). The MCA highlighted the advantages and disadvantages of each of the water sources based on these judgment criteria by providing scores from ++ (very positively judged) to – (very negatively judged (Table x). Therefore, water sources can be compared with each other.

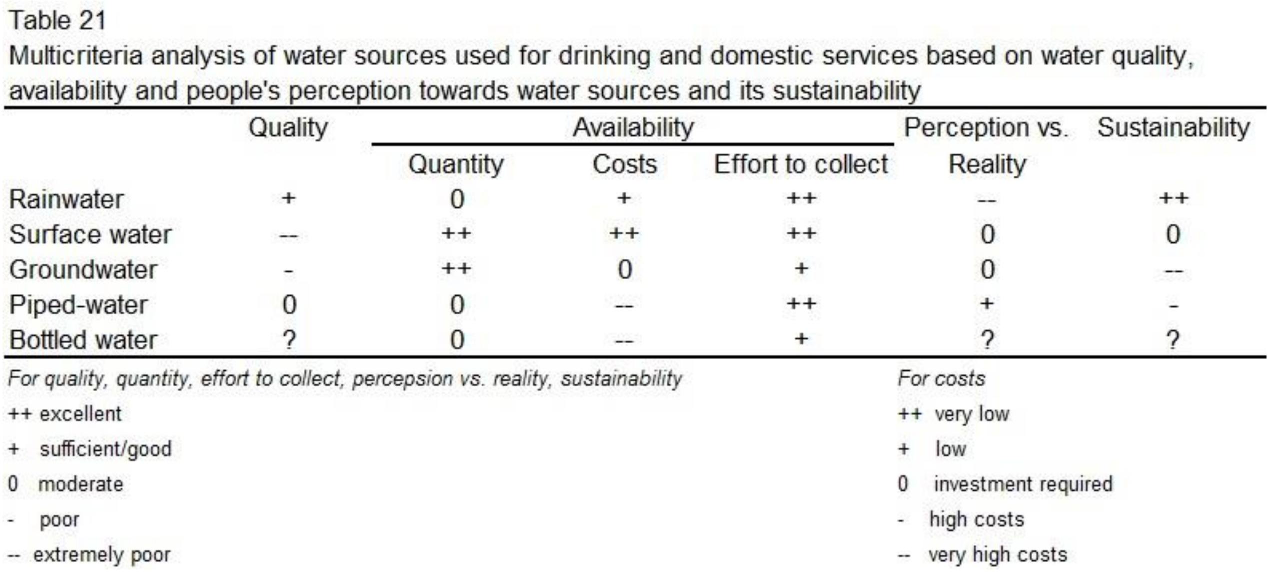


Table 21
Multicriteria analysis of water sources used for drinking and domestic services based on water quality, availability and people's perception towards water sources and its sustainability

	Quality	Availability			Perception vs. Reality	Sustainability
		Quantity	Costs	Effort to collect		
Rainwater	+	0	+	++	--	++
Surface water	--	++	++	++	0	0
Groundwater	-	++	0	+	0	--
Piped-water	0	0	--	++	+	-
Bottled water	?	0	--	+	?	?

For quality, quantity, effort to collect, percepsion vs. reality, sustainability
++ excellent
+ sufficient/good
0 moderate
- poor
-- extremely poor

For costs
++ very low
+ low
0 investment required
- high costs
-- very high costs

8.1.1 Water quality, availability and perceptions

Surface- and groundwater

The highest health-related risks associated with water sources used for drinking and domestic services were expected for surface- and groundwater. The results of this study show that these water sources are indeed severely contaminated and intensively used for both drinking and domestic purposes. Thus, their usage could lead to serious health-related concerns.

Surface water contains high concentrations of various pollutants including nutrients, metals and microbial indicator bacteria caused by urban and industrial effluents, soil leaching and agricultural (point and diffuse) sources although large spatial differences were observed. Surface water quality maps of Can Tho/Hau Giang provinces show the highest nutrient (NH_4) and total coliform concentrations near urbanized areas. DO concentrations are significantly lower in urbanized areas compared to areas with other land-use characteristics. In contrast, lowest nutrient, metal and coliform concentrations are visible in orchards dominated areas since trees may function as natural filters. However, even at those locations guidelines levels are frequently exceeded indicating severe health-risks when the water is used without proper treatment. The surface water quality maps also show elevated nutrient concentrations near fish farms. The tidal regime also has a significant effect on surface water quality by influencing the residence rate of water in a particular area. In general, locations with a large distance to main rivers are less-intensively refreshed by river water compared to locations close to main rivers, resulting in an accumulation of pollutants. This pattern is clearly visible for Mn but also found for other water quality parameters like COD. Moreover, surface water quality is also influenced by the distance to the coast. In general, surface water in coastal regions is more saline compared to inland regions due to sea water intrusion which makes them unsuitable for drinking and other domestic services.

Although locations with groundwater of decent quality were found and visualized through mapping techniques, a majority of the studied areas in the MD showed elevated concentrations of metals (As, Fe, Mn, Ba) and NH_4, exceeding drinking water guidelines in groundwater. Groundwater quality probability maps for NH_4 and Mn show that concentrations of these parameters can be exceeded at almost all investigated sites (Can Tho, Hau Giang, Soc Trang). Although most of the studied sites do have As concentrations below WHO drinking water guidelines, (potential) hot-spot areas were detected including within and around Can Tho City. Elevated chloride concentrations in groundwater hamper its use for drinking and other domestic services. Cl hot-spot areas in groundwater were found in Hau Giang and Soc Trang provinces due to over-exploitation and saline intrusion. In addition, pathogens were observed in groundwater which is likely caused by improper construction of wells causing pollution of groundwater by leaching as well as a variety of other causes.

Nevertheless, surface- and groundwater have clear advantages above other potential drinking and domestic water sources which could explain their preference by local populations. First of all, the MD has a large density of natural and man-made canals which contain water all year round, which is easy to collect by households and is a resource almost free of charge. For surface water, only small investments such as storage jars, alum to remove suspended solids and disinfectants are required although some people even use it directly from canals (i.e. for washing). Secondly, groundwater sources are abundant and relatively easy to reach with own-dug wells to depths of around 100 meter (2nd aquifer). Investment costs to dig a groundwater well are around 2 million VND (75 euro), which is affordable given the fact that this is usually a one-time investment. Additional costs are the electricity and maintenance for electrical pumps although groundwater wells with hand-pump do not have these additional costs. In general, the availability of surface- and groundwater sources is better to rural inhabitants in the MD compared with other water sources. Rainwater is not available all year round since no or limited rainfall events occur in the dry season while piped- and bottled water are too expensive for most households in this region and/or not available in sufficient quantities required for daily needs.

Although surface- and groundwater are severely contaminated and used intensively, health-risks associated with the daily use of these sources is reduced due to the fact that people rightly perceive these sources as contaminated based on the psychical conditions of water such as color and smell. Thus, households apply treatment to these water sources prior to consumption. Almost all households using surface- and groundwater for drinking claimed to use alum treatment and/or disinfect surface water prior to consumption (via e.g. boiling). For surface water, the applied household level treatments (alum and boiling) significantly reduced pollutant concentrations for nutrients, metals and pathogens. However, salinity levels as well as some metals (As) were not significantly reduced by these treatment processes. Groundwater in the MD usually has a typical metallic smell due to elevated concentrations of Fe and Mn. For some households, this is a reason to reject groundwater for drinking. Other households expose groundwater in jars and other storage containers to the air for several days after pumping and treat it will alum in an attempt to ‘improve’ the quality prior to consumption. Exposure to the open air and treatment with alum causes settlement of metals like Fe and Mn and indeed reduces the smell of water. Also NH_4 concentrations are significantly lower in household stored groundwater compared to untreated groundwater. Although surface- and groundwater are usually perceived as polluted which matches the reality and triggers treatment action, there is still a considerable health-risks associated with the daily use of these water sources which need to be addressed urgently in order to reduce incidents of water-related diseases. Firstly, people only treat the water used for drinking while water used for other domestic purposes such as washing and cleaning (also vegetables and cutleries) remain untreated. Secondly, As contamination is not removed effectively by the above mentioned treatment techniques. Thus, treated surface- and/or groundwater may be perceived as clean and safe for drinking although As concentrations above drinking water guidelines may persist. Thirdly, household treated groundwater contains higher concentrations of pathogens than untreated groundwater which is a health-risk when people do not boil these water sources prior to consumption. In order to further decrease health-risks associated with surface- and groundwater a number of measures should be put in place by authorities in the MD: i) water treatment facilities are needed to improve the quality of effluents reaching natural water bodies, ii) surface- and groundwater should additionally be treated with i.e. with stone, sand (with zero valent iron layers) and active coal filters to reduce concentrations of As, Fe, Mn and pathogens in order to make these sources potable.

Harvested rainwater and piped-water

It was expected that the health-risk associated with the daily use of rain- and piped water by rural inhabitants of the MD would be lower compared to surface- and groundwater. Indeed, the quality of both household harvested rainwater and piped-water is better compared to surface- and groundwater. However, harvested rainwater is contaminated with Pb and pathogens via the collection system (roof and gutters) and due to improper storage and handling practices. At the same time, it intensively used since it is relatively easy and cheap to access via roofs-harvest (except in dry season due to lack of rainfall events). Harvested rainwater is generally perceived as a safe and clean water source since it has no smell, taste and odor. Therefore most people using harvested rainwater for drinking do not treat rainwater prior to consumption. Due to a combination of microbial pollution of harvested rainwater (which likely occur during harvest and storage) and people’s perception of this source as a clean water source, it pose the highest health-related risk of all investigated water sources for pathogens. In this context, authorities should urgently set-up educational programs to raise awareness regarding pollution in harvested rainwater given the large reliance on this source for drinking. Harvested rainwater should be disinfected regardless of whether it is perceived as clean or not. Moreover, gutters should be kept free from lead to prevent the presence of this toxic metal in harvested rainwater. When those conditions are met, harvested rainwater could be one of the best available water sources for drinking and even for domestic purposes in the MD although this is certainly not the case yet.

For piped-water, some samples were polluted with multiple contaminants while other samples met all the water quality criteria set by the WHO and national drinking water guidelines. Differences between intake source of piped-water supply stations (surface- or groundwater) and possible leakages in transportation pipes are two main reasons for differences in water quality between investigated water supply stations. Although piped-water is treated by the supply station prior to delivery, it is generally not perceived as a safe drinking water source and people usually disinfect it via boiling. Thus, health-risk associated with pathogens contamination via piped-water is low. Nevertheless, there are main constraints regarding the use of piped-water in rural areas of the MD. First of all, most rural communities in the MD do not even have the possibility to connect to piped-water since a water supply company is not present. Secondly, when a piped-water supply station is available, the connectivity rate is low due to high connection fees and costs of water, poor perceived quality/quantity and people’s preference for other water sources for drinking and domestic purposes. Thus, very few people in rural areas of the MD actually use piped-water for daily needs.

Bottled water

From the ten investigated bottled water samples, none exceeded drinking water guidelines for the contaminants considered in this research. However, since hundreds of water brands are present in the MD, it is not possible to reach an accurate conclusion regarding the quality and safety of bottled water.

More investigation of bottled water quality is urgently required since many inhabitants use this source for drinking. Bottled water is however not the main drinking water source people depend on due to its relatively high costs. Therefore, bottled water is used only for vulnerable family members (children and elderly people) or temporarily when i.e. rainwater is not available during the dry season. Only large scale fish farmers in rural areas of the MD indicated to completely rely on this water source for drinking although this is a relatively small proportion of the MD population.

8.1.2 Sustainability of water sources with respect to drinking and domestic services

A sustainable use of water sources is important in order to secure sufficient clean and safe water sources for future generations.

In this context, surface- and rainwater are relatively positively judged for the MD. Surface water is and can be intensively used for various services including drinking and domestic use due to a continuous flow of fresh water from upstream countries all year round. Only, in and near coastal areas the usage of surface water may be difficult due to salt water intrusion from the sea. On the other hand, continuous pollution of surface water threatens the use for drinking and domestic services dramatically.

Rainwater is also available in large quantities due to monsoonal rainfall events in the wet season and is an inexhaustible water sources and therefore regarded as the most sustainable water source for drinking and domestic purposes. The use of rainwater for drinking and domestic services is only limited by household storage capacity.

In contrast, the current use of groundwater in the MD is not sustainable. Groundwater sources are under serious pressure due to their use for irrigation of crops, usage in drinking water supply stations and domestic purposes by rural inhabitants. These activities result in a continuous drop in groundwater levels and enhance saline intrusion in coastal areas. At some locations in the MD, groundwater is already completely saline and not suitable for any purpose. Given the fact that desalinization techniques to make salt water potable are too expensive for the MD inhabitants, there is an urgent need to wisely use this water source. This is especially the case for fresh groundwater sources in coastal areas where alternative water sources are scarce due to sea water intrusion. Therefore, the use of groundwater for irrigation should be drastically reduced. In coastal areas for example, the cultivation of more saline resistant crops should be considered to decrease the demand on fresh groundwater. In addition, households should also be made aware that groundwater is not an unlimited water source and that it should be used sparingly in order to secure sufficient clean groundwater sources for future generations.

For piped-water, a sustainable supply station can only exist when sufficient paid household connections are present in order to supply and treat the water and maintain the supply station. In addition, the intake source should be of a constant quality. In the MD, there are several supply stations delivering water to respective communities that meet these criteria especially in larger villages and cities. Unfortunately, this is not the case for most water supply stations in rural areas of the MD. Some of these supply stations using groundwater are affected by saline intrusion of groundwater which makes it unsuitable for drinking. In addition, some supply stations are not cost-efficient due to low connectivity rates. As a result, various water supply stations are not properly maintained and/or completely abandoned and people start using other water sources for daily purposes like surface- and groundwater.

Therefore, future developments of piped-water supply stations in rural areas of the MD should be judged carefully as piped-water may not be the main solution to provide safe, clean and sufficient water to rural communities. The sustainability of bottled water should be further assessed with respect to waste collection (empty bottles) and sufficient supply to its inhabitants.

8.2 Recommended water sources use for drinking and domestic purposes

Authorities in Vietnam strongly encourage the development of piped-water supply stations to provide safe and sufficient water sources for its inhabitants. Moreover, many international organizations like the World Bank and foreign countries provide aid to construct piped-water supply stations. For cities, larger villages and other densely populated areas, the construction of a piped-water supply can indeed serve as a reliable and safe source of water for daily purposes. However, in more remote areas where households are scattered in the landscape (which is more common in the MD), other water sources for drinking and domestic purposes are recommended (Fig. 24).

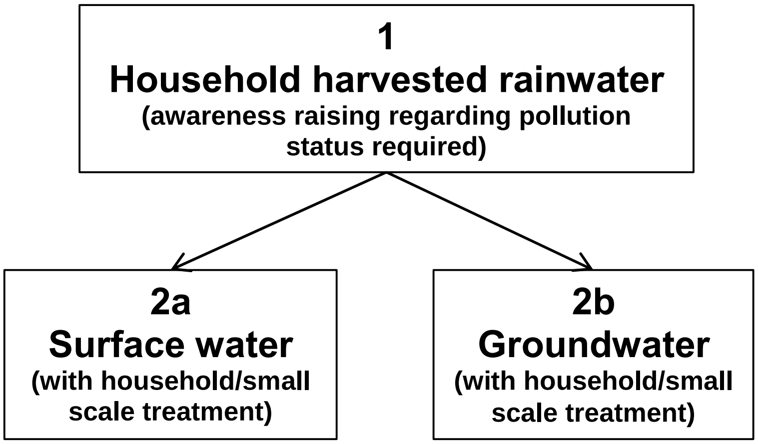


Figure 24 – suggested water sources use for rural (scattered) communities in the MD with respect to drinking and domestic services. Note: bottled water is not included since this is an additional drinking water source.

Although household harvested rainwater was found to have the highest health-related risks for pathogens it is the best available water source for rural communities in the MD for drinking. The quality of household harvested rainwater is generally better compared to other water sources, cheap and easy to collect and widely available. The high health-related risks can furthermore be substantially reduced when people are made aware of pollution levels and improper handling practices; and can thus apply disinfection prior to use. When rainwater is not available, households are advised to use both surface- and groundwater. Surface water could function for domestic purposes when treated with alum and disinfected prior to use. However, the use of surface water for drinking should be limited due to complex pollution status of this water source. However, for washing, cleaning and cooking treated surface water could be a decent and sustainable water source. It is furthermore recommended to develop surface water quality maps for the entire MD, similar as for Can Tho and Hau Giang provinces in this study. Such maps could be developed by selecting water quality monitoring stations in representative land-use and soil type systems within different hydrological areas (inland/coastal regions), using data from the different provincial water quality monitoring stations. These maps could indicate optimal locations for surface water extraction. Groundwater could be used for drinking after treatment with (zero valent equipped) sand-filters and disinfection via boiling or chlorine prior to consumption. The development of groundwater quality probability maps can help to identify suitable locations for groundwater extraction. Nevertheless, the use of groundwater for domestic services should be limited in all cases due to intensive pressure on this water source.

In general, the use and development of sophisticated piped-water supply stations is not recommended in rural (scattered) areas in the MD since it was observed that many supply stations do not supply water in sufficient quantities and quality. However, development of small (decentralized) water treatment facilities at the household level to make surface- and/or groundwater sources potable could be a promising way to provide safe and sufficient water to scattered households in the rural MD. Such treatment facilities could be equipped with low-tech and cheap filters like sand and stone beds with zero-valent iron and aeration beds.

Authorities in Vietnam, international organizations and foreign aid programs should focus more on those measurements to provide safe and clean water for remote households in the MD instead of investing in large water supply stations. In addition, authorities and foreign aid programs should also make investments to increase rainwater storage capacity for rural communities to make more effective use of this natural and freely accessible water source. These measures could be efficient ways to supply safe water for present and future generations and significantly reduce incident of water-related diseases in poor regions of the MD.

8.3 Outlook

The present status of drinking water quality and health-risks associated with the use of water for drinking and other domestic purposes is of concern and needs to be urgently addressed. Several developments in the region as well as climate change will have further impacts on future water quality which also needs to be addressed in order to secure safe and sufficient water sources for the next generations.

Rising sea levels due to climate change is a main threat to fresh water sources in delta systems worldwide and the MD is not an exception. Further salinity intrusion of surface water in the MD is a main threat since saline water is unsuitable for any domestic purpose. In the coastal Soc Trang province for example, surface water is not used at all and many inhabitants struggle to collect fresh water for irrigation, drinking and other domestic services. The development of hydropower dams in upstream countries of the Mekong River Basin will affect the flow regime and may potentially have a significant impact on water quality as well. In this context, it is strongly recommended to increase the storage capacity of rainwater to secure a sufficient fresh water resource when those differences in surface water quality/quantity actually occur. Groundwater is intensively used for multiple purposes, resulting in a constant decline of groundwater levels. A continuous drop in groundwater level enhances salinization from sea water as well as from seepage (more saline) water from deeper aquifers. Moreover, over-exploitation may lead to clay compaction within aquifers and aquitards which could result in the release of arsenic-rich compounds. Thus, current groundwater sources with As concentrations below WHO and Vietnamese drinking water guidelines may become more contaminated with this metalloid as a result of this process in the future. A shift in the use from groundwater to rainwater may decrease the pressure on groundwater sources and declines the risks of non-potable groundwater sources.

Although surface- and groundwater sources are under pressure and their use should be limited (in particular for groundwater), the population in the MD will always be dependent on these water sources for various services. In order to maintain and enhance a decent quality/quantity of these water sources, it is advised to develop yearly surface- and groundwater quality maps for the MD based on water quality monitoring data conducted by the Vietnamese governmental organizations like the DONRE’s. Yearly water quality monitoring programs and water quality maps provide insight into hot-spot areas of pollution as well as areas with water of a good quality (compared to WHO/Vietnamese water quality standards). Furthermore, trends in water quality in time can be observed. Thus water quality monitoring and maps are strong tools to sustainably manage water sources in order to serve the needs for present and future generations.

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ANNEXES

Annex 1: effects of soil type, land-use and the tidal regime on surface water quality

A1.1 Soil types

The main soil types of the MD include alluvial soils, acid sulphate soils and saline intruded soils. These soils types have various characteristics with respect to its acidity, conductivity, organic matter percentages and concentrations of salts and metals. An overview of some characteristics of representative soil types are presented in Table A1.1.

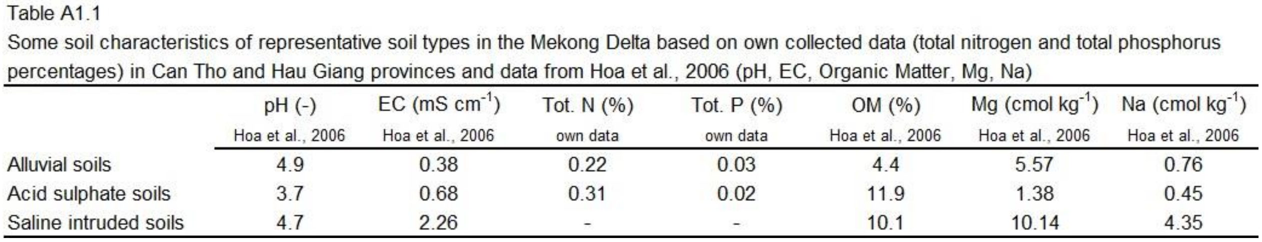

Table A1.1

Some soil characteristics of representative soil types in the Mekong Delta based on own collected data (total nitrogen and total phosphorus percentages) in Can Tho and Hau Giang provinces and data from Hoa et al., 2006 (pH, EC, Organic Matter, Mg, Na)

	pH (-) Hoa et al., 2006	EC (mS cm^{-1}) Hoa et al., 2006	Tot. N (%) own data	Tot. P (%) own data	OM (%) Hoa et al., 2006	Mg (cmol kg^{-1}) Hoa et al., 2006	Na (cmol kg^{-1}) Hoa et al., 2006
Alluvial soils	4.9	0.38	0.22	0.03	4.4	5.57	0.76
Acid sulphate soils	3.7	0.68	0.31	0.02	11.9	1.38	0.45
Saline intruded soils	4.7	2.26	-	-	10.1	10.14	4.35

As expected, the acid sulphate soils show the lowest pH levels compared to the other representative soil types. The concentrations of Mg and Na were also lower in acid sulphate soils. The highest levels of EC are present in saline intruded soils most probably due to its relatively high content of salts (Na) compared to other soil types. Highest pH values are present in alluvial soils although organic matter percentages in these soils is significantly lower compared to acid sulphate- and saline intruded soil types. The percentages of total nitrogen (N tot.) and total phosphorus (P tot.) did not show large differences between alluvial and acid sulphate soils, although these parameters were not defined in saline intruded soil types.

Soil leaching was shown to be one of the explaining factors for spatial variability in water quality (based on the PCA analysis). This was particularly the case for metals. It is expected that soil leaching is influenced by soil type. Therefore, four water quality parameters which were also expected to be influenced by soil type were plotted separately for 4 different soil types (Fig. A1).

The lowest pH values were recorded as expected in the moderate acid sulphate soil (ASS) region (Hau Giang province) although differences with the other regions are relatively small (< 0.5 pH units) except for the saline soils in Soc Trang due to high alkalinity of intruded sea water. The lowest pH values in the moderate ASS were observed in April (pH = 6.4) and suggests the influence of heavy rains at the beginning of the rainy season that flush out accumulated acids from the soil. The accumulation of acids could be the result of pyrite reduction that is expected to occur mainly during the dry season due to lower water levels that result in oxidation of top-soils. A similar pattern of lower pH values in the canals of the MD at the start of the wet season was also found in the Plain of Reeds in Vietnam, although pH values decreased to 3 (Husson *et al.*, 2000). Such levels were not observed in this study. Hoa *et al.* (2007) found pH values decreasing to < 3.5 at the start of the rainy season in various regions of the MD which also contradicts observed pH values in this study. Both Husson *et al.* (2000) and Hoa *et al.* (2007) concluded that as a result of those low pH values, leaching of metals occurred resulting in maximum concentrations of Fe and Al of 182 mg L^{-1} and 104 mg L^{-1}, respectively. These findings differ from our study that showed Al and Fe concentrations between 2 – 4 mg L^{-1}. The higher pH values and lower concentrations of metals in this study compared with other studies in the MD suggest a strong variability in the presence of ASS in the region and indicate that the selected areas in our study are not severely affected by these soil types. This is confirmed by an investigation of the acidity of soils in Can Tho and Hau Giang provinces were soil pH values ranged between 4.2 and 4.3 indicating its slighter acidity in comparison with typical acid sulphate soils in the MD (Table A1.1). The presence of other metals did not or only slightly vary between the study sites and show similar patterns to that of Cr.

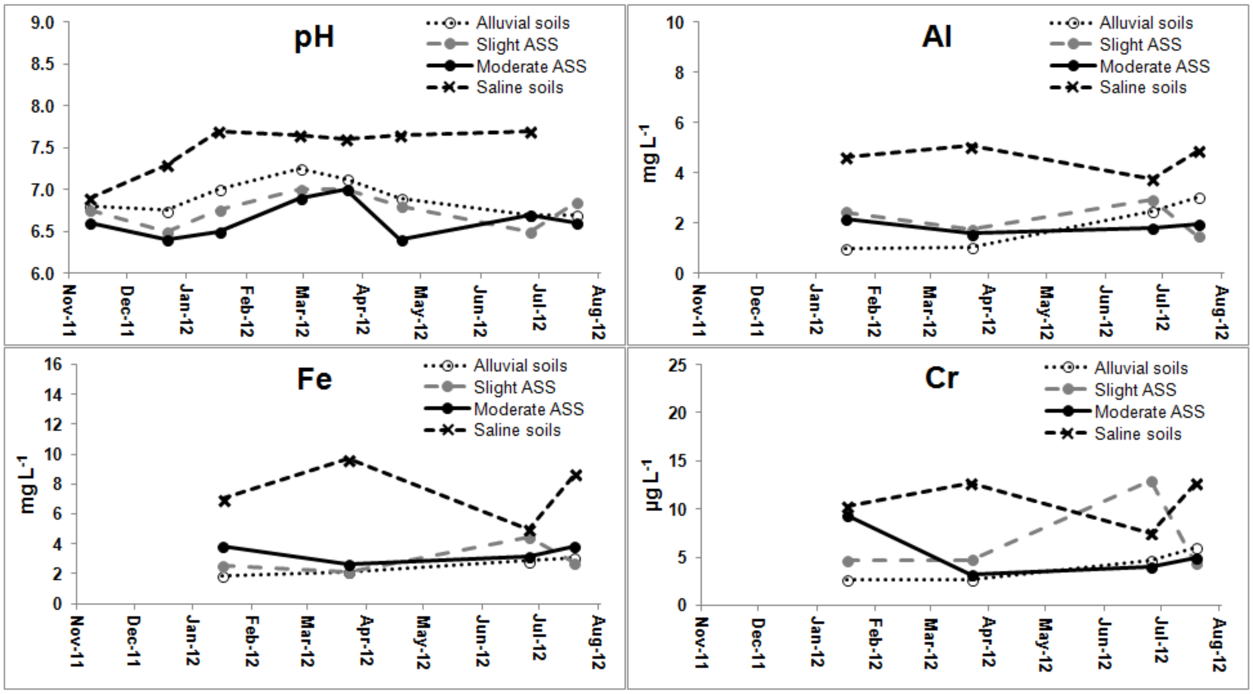

Figure A1 – Median pH values and Al, Fe and Cr concentrations in surface waters of secondary canals at four representative soil type regions in the Mekong Delta. The symbols in the graphs indicate the measurement dates and are connected with straight lines. Note the different unit range for Cr in comparison with Al and Fe and the differences in measurement frequency between pH and the presented metals.

A1.2 Land-use

The influence of different land-use systems on surface water quality was further assessed by the Pearson Correlation test. For this analysis, annual median concentration/values were compared with the presence of different land-use system. To identify land-use systems, a digital map covering the inland regions (Can Tho and partially of Hau Giang provinces) was used. A total of twenty sampling locations fitted within the extent of the map and were used for the analysis. Around these sampling locations, squares representing various distances (150, 350, 550, 750, 950 m) were constructed and the percentages of the different land-use systems were derived in each of them. Then, relationships between water quality and land-use was visualized graphically and a correlation analysis was carried out (R^2) for each square size, to investigate which square size showed strongest relationships between water quality and land-use. This analysis revealed the strongest relationships for the 750 m squares. In order to fulfill the criteria of the Pearson Correlation test (equal variance, normal distribution), most concentrations/levels of the investigated parameters were log-transformed. The annual median concentrations/values were then statistically compared with the percentages of different land-use systems. This analysis revealed three land-use systems that showed significant relationships with surface water quality in the lower order canals and are presented in table A1.2.

The results of the analysis confirm the strong relationship between urbanization and aquaculture with a large variety of selected water quality parameters. The presence of fruit orchards were also found to be significantly correlated to water quality parameters. However, other land-use systems such as planted trees, rice fields, other agricultural systems and gardens were not found to have significant relationships with the selected water quality parameters and are therefore not presented.

Locations with dense urbanization show significantly higher levels of EC and pH and higher concentrations of TDS, NH_4, Cl, Na, Ba, Cd, Cu, Zn and coliforms in comparison with other land-use systems whereas the concentrations of DO and NO_3 were lower. This finding is in line with the PCA analysis which also revealed a correlation between these parameters which was identified as the impact of urbanization. In general, the presence of these substances indicates that water is contaminated with untreated waste water. On the contrary, most of the investigated water quality parameters in our study showed lowest concentrations in fruit orchards areas, except for NO_3.

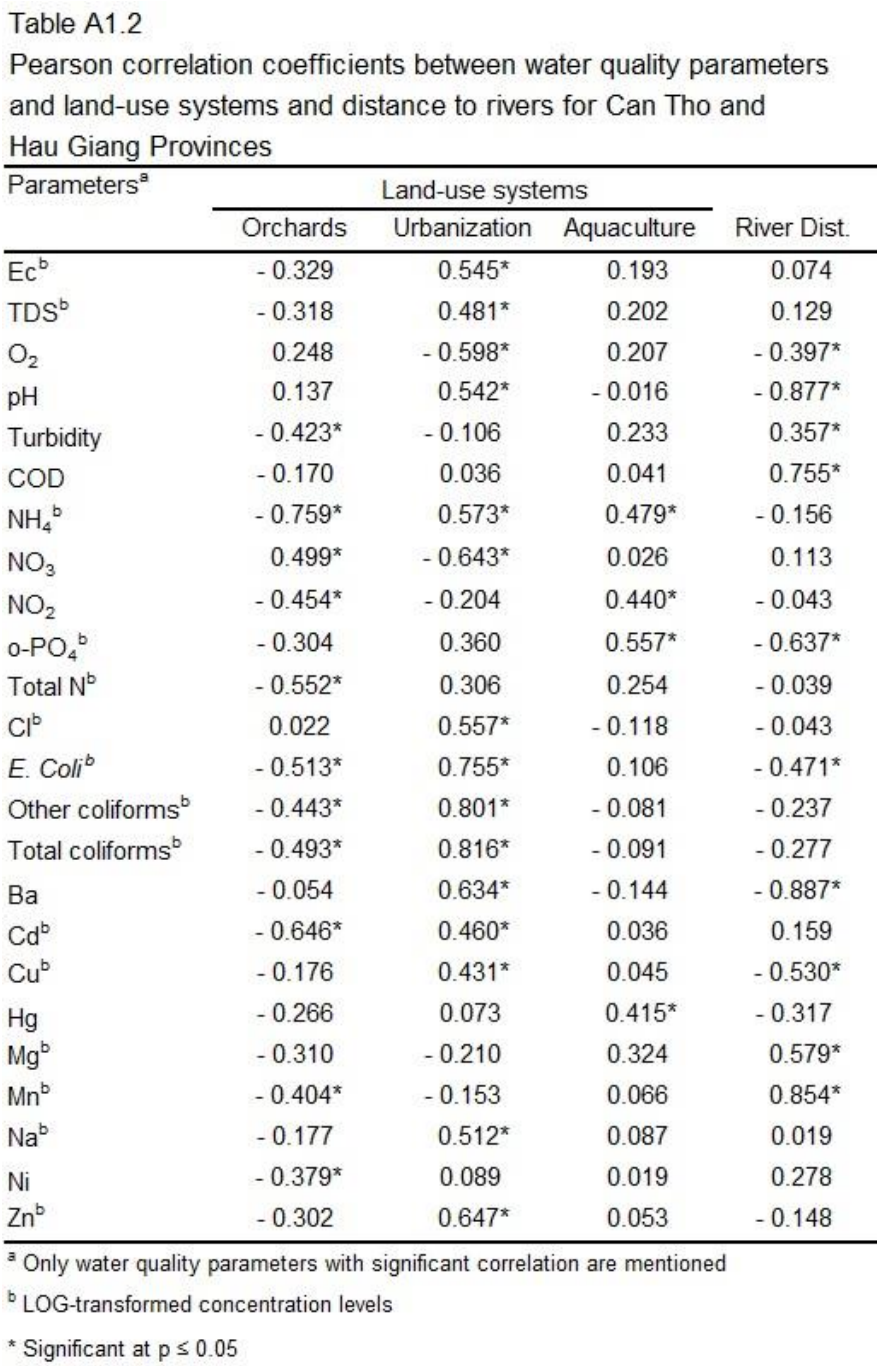

Table A1.2

Pearson correlation coefficients between water quality parameters and land-use systems and distance to rivers for Can Tho and Hau Giang Provinces

Parameters[a]	Land-use systems			
	Orchards	Urbanization	Aquaculture	River Dist.
Ec[b]	- 0.329	0.545*	0.193	0.074
TDS[b]	- 0.318	0.481*	0.202	0.129
O_2	0.248	- 0.598*	0.207	- 0.397*
pH	0.137	0.542*	- 0.016	- 0.877*
Turbidity	- 0.423*	- 0.106	0.233	0.357*
COD	- 0.170	0.036	0.041	0.755*
NH_4[b]	- 0.759*	0.573*	0.479*	- 0.156
NO_3	0.499*	- 0.643*	0.026	0.113
NO_2	- 0.454*	- 0.204	0.440*	- 0.043
o-PO_4[b]	- 0.304	0.360	0.557*	- 0.637*
Total N[b]	- 0.552*	0.306	0.254	- 0.039
Cl[b]	0.022	0.557*	- 0.118	- 0.043
E. Coli[b]	- 0.513*	0.755*	0.106	- 0.471*
Other coliforms[b]	- 0.443*	0.801*	- 0.081	- 0.237
Total coliforms[b]	- 0.493*	0.816*	- 0.091	- 0.277
Ba	- 0.054	0.634*	- 0.144	- 0.887*
Cd[b]	- 0.646*	0.460*	0.036	0.159
Cu[b]	- 0.176	0.431*	0.045	- 0.530*
Hg	- 0.266	0.073	0.415*	- 0.317
Mg[b]	- 0.310	- 0.210	0.324	0.579*
Mn[b]	- 0.404*	- 0.153	0.066	0.854*
Na[b]	- 0.177	0.512*	0.087	0.019
Ni	- 0.379*	0.089	0.019	0.278
Zn[b]	- 0.302	0.647*	0.053	- 0.148

[a] Only water quality parameters with significant correlation are mentioned

[b] LOG-transformed concentration levels

* Significant at $p \leq 0.05$

The generally lower observed concentration of NH_4 and higher concentrations of NO_3 in orchards areas could be explained by the presence of raised beds for fruit trees plantations which is not present elsewhere in the MD. The raised beds of around 1 meter above surface waters creates aerobic conditions in the soils which enhances nitrification processes and reduces the concentration of NH_4 in surface water. This is confirmed by the significantly higher concentrations of NO_3 within orchards areas. These processes do not occur in other land-use systems that are mostly flooded such as rice fields where nitrification is expected to be limited. A further explanation of generally lower pollutant concentrations in orchards could be the result of different sanitation usage within orchard areas. At most locations, sewage water and husbandry effluents are discharged directly to the surface waters with e.g. latrines constructed directly above the canals. However within the orchards areas, it was observed that latrines as well as husbandry effluents are often discharged within the plantations were the trees can act as natural filters which lead to a decrease of household related emissions to the surface water. The positive correlations between the percentage of aquaculture and concentrations of NH_4, NO_2, o-PO_4 and Hg are also in line with PCA analysis. This confirms the influence of emissions of waste water from fish ponds to the canals.

A1.3 Tidal regime

Except for the relationship between land-use and surface water quality, Pearson Correlation coefficients were also defined for the relationship between water quality concentrations/levels at the twenty selected locations and distance to main rivers (Table S1). Since a pattern of lower flow velocities, inducing decreased mixing of water during low tides, was observed at locations further inland, the river distance was selected as representative parameter for this effect. The distance of a location to a main river, was found to significantly affect the quality of surface water for most of the selected parameters. Positive correlations between river distance with turbidity levels and concentrations of COD, Mg and Mn were found, indicating highest concentrations/values at locations further away from rivers. On the other hand, negative correlations were found for pH values and DO, o-PO_4, Ba, Cu and *E. coli* concentrations. Higher COD at locations further away from main rivers suggest the accumulation of organic pollutants when there is poor mixing with fresh water. Similarly, the accumulation of pollutants could also contribute to the positive correlation between river distance and turbidity levels. As expected, an opposite pattern is observed for the concentrations of DO which shows lower concentrations at locations far from rivers. The river distance is also an important factor for the concentrations of Mn in surface water. Most probably, Mn continuously leach from soil to surface water resulting in accumulated concentrations when there is little mixing with fresh water. A similar pattern, but to a lower extent, is also observed for Mg. Another possible reason for this pattern is the observed lower pH values at inland locations (Hau Giang province). Acid conditions of soils may result in increased leaching of metals to surface water. However, similar patterns were then expected for the concentrations of other earth metals like Al, Fe and Cr, which was not observed in this study. Therefore, more research is required to determine the origin and causes of accumulation of Mn that leads to exceeding guideline values at many locations in the MD.

Cu and *E. coli* concentrations also show inverse significant relationships with river distance. However, these water quality parameters are also related to urbanized areas. Since a large urbanized agglomeration (Can Tho City) is located near a main river (Hau River), this could wrongly influence the inverse correlation between river distance and concentrations of Cu and *E. coli.*

Annex 2: local variability of groundwater quality

A2.1 Materials and methods

Local variability of groundwater quality was assessed at three geographically different locations in the Can Tho and Hau Giang provinces in (Fig. A2.1). Ten groundwater samples were collected in O'Mon district in Can Tho province (location 1), thirteen groundwater samples were collected in Co Do distict in Can Tho province (location 2) and twelve groundwater samples were collected in Kinh Cung in Hau Giang province (location 3) between February and April 2012 (dry season in the MD). The surface areas of each selected sites were all smaller than 9 km^2 to assess local variability of groundwater quality. The selected groundwater wells were purged for 10 minutes and then analyzed for electrical conductivity (EC) in the field directly.

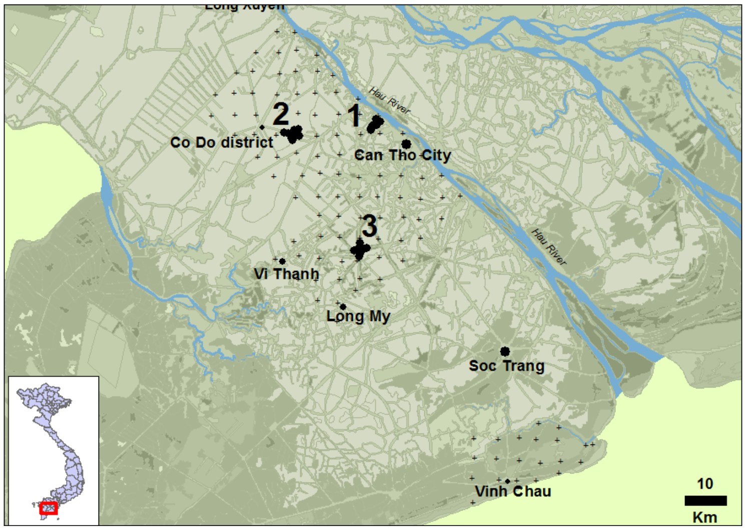

Figure A2.1 – Visualization of the case study sites to assess local variability in groundwater quality.
+: regular groundwater monitoring locations collected between July – September 2012.

A2.2 Results

Groundwater quality was found to vary between the selected regions with lowest observed EC levels in the Co Do district while the highest EC levels were found in the O'Mon district. However, groundwater quality was also found to significantly vary within the selected locations indicating a strong local variability (Fig. A2.2).

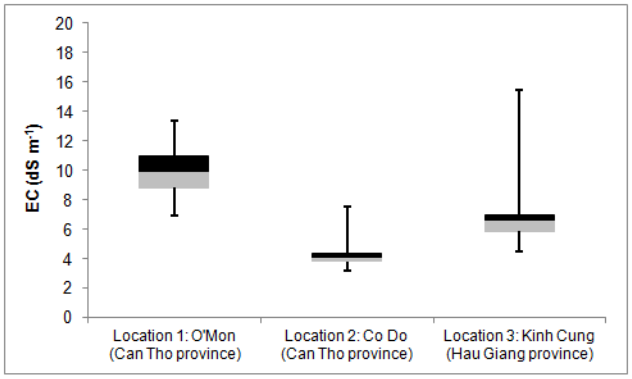

Figure A2.2 – Boxplots of EC levels at the three selected regions to investigate local variability in groundwater quality

It was expected that groundwater quality (EC levels) would be similar within a small region. However, the difference in minimum and maximum EC levels within the three regions differed by a factor of 2 (Co Do) to 4 (Kinh Cung). These high variations have implications for the development of groundwater quality maps and hot-spot identification. Regular interpolation techniques like kriging and inverse distance weighting are only based on the measured average or median concentrations and do not include the variability of the datasets. Such interpolation techniques will most likely under- or overestimate the actual groundwater quality at any given location. However, GGS is a simulation technique that considers variability of datasets and could therefore be useful for the groundwater quality dataset in the MD to identify (possible) hot-spot areas of pollution.