Assmuth Timo, Simola Antti, Pitkänen Tarja, Lyytimäki Jari, Huttula Timo (2016). Integrated frameworks for assessing and managing health risks in the context of managed aquifer recharge with river water. Integrated Environmental Assessment and Management 12(1): 160-173. https://doi.org/10.1002/ieam.1660

Integrated frameworks for assessing and managing health risks in the context of managed aquifer recharge with river water

ABSTRACT

Integrated assessment and management of water resources for the supply of potable water is increasingly important in light of projected water scarcity in many parts of the world. This article develops frameworks for regional-level waterborne human health risk assessment of chemical and microbiological contamination to aid water management, incorporating economic aspects of health risks. Managed aquifer recharge with surface water from a river in Southern Finland is used as an illustrative case. With a starting point in watershed governance, stakeholder concerns, and value-at-risk concepts, we merge common methods for integrative health risk analysis of contaminants to describe risks and impacts dynamically and broadly. This involves structuring analyses along the risk chain: sources—releases—environmental transport and fate—exposures—health effects—socio-economic impacts—management responses. Risks attributed to contaminants are embedded in other risks, such as contaminants from other sources, and related to benefits from improved water quality. A set of models along this risk chain in the case is presented. Fundamental issues in the assessment are identified, including 1) framing of risks, scenarios, and choices; 2) interaction of models and empirical information; 3) time dimension; 4) distributions of risks and benefits; and 5) uncertainties about risks and controls. We find that all these combine objective and subjective aspects, and involve value judgments and policy choices. We conclude with proposals for overcoming conceptual and functional divides and lock-ins to improve modeling, assessment, and management of complex water supply schemes, especially by reflective solution-oriented interdisciplinary and multi-actor deliberation.

Keywords:

Integrated assessment; Health; Managed aquifer recharge; Human health risk assessment; Water management

INTRODUCTION

Contamination of water resources represents an important and complex risk in conditions of both water scarcity and abundance (CEC 2012). Although new technologies have reduced many risks and brought many benefits, new risks have emerged due to new products, to changing natural and technological conditions, and to analytical capabilities. Water resources are thus threatened by harmful substances such as pharmaceuticals (Loos et al. 2010; Stuart et al. 2012) and microbes such as viruses (Pitkänen et al. 2013).

This article addresses contamination risks in the context of potable water provided by Managed Aquifer Recharge (MAR) with surface water (Artimo et al. 2003; Dillon 2005). This context differs from water recycling based on direct or indirect reuse of wastewater (Ayuso-Gabella et al. 2011; Bekele et al. 2011) as well as from drinking water treatment at surface water works (Huerta-Fontela et al. 2011). The risks, benefits, costs, and other impacts of such activities are thus variable (Roberts 2010). The risks, however, have also commonalities and so do assessment and management approaches (Power and McCarty 1998; Jardine et al. 2003). Common key issues include the reliability and sustainability (ecological, economic, and social) of resource use (Ison et al. 2007).

Managed Aquifer Recharge systems can treat many contaminants relatively efficiently, depending on the case (Rodriquez et al. 2009; Page, Dillon, Toze, Bixio et al. 2010; Page, Dillon, Toze, Sidhu 2010; Laws et al. 2011; WHO 2011b). The key issue is what limitations, due also to breakthrough lags and abnormal conditions, there are in this risk reduction efficiency and capacity, and what implications these have for the costs and benefits of alternative management strategies (WHO 2012).

Extensive water use systems are typical cases for integrated risk analysis and governance (Brouwer and Hofkes 2008). Multicriteria methods, also probabilistic and dynamic, have been applied also to groundwater contamination (Kaunas and Haimes 1985; Khadam and Kaluarachchi 2003; Siegfried et al. 2009). Yet, the risks have seldom been treated broadly. Standard approaches to risks of water contamination have insufficiently considered the multidimensionality of risks (USEPA 2000, 2012; IRGC 2006; ECHA 2008). Health risks in particular are subject to multiple concerns and controversies, and analytical approaches need to account for these (Khan and Gerrard 2006; Jalba et al. 2010; Austin et al. 2012).

Some health risks of microbiological contamination of drinking water are well-recognized (Toze et al. 2010). More chemicals and their effects have been studied than ever before (Kumar and Xagoraraki 2010; Schriks et al. 2010; Chowdhury 2013), even in groundwater and MAR (Loos et al. 2010; Stuart et al. 2012). However, the analyses and risk assessments have been limited as to system parts, contaminants, processes, and types of risks. Socio-economic aspects are relatively seldom considered, even though they are core elements of risks and their management. Cost–benefit analyses (Ward 2012) and economic models (Wittver 2012) have been applied to water resource management including groundwater (NRC 1997; Botzan et al. 1999) and contamination of potable water (Urkiaga et al. 2008), but the focus has rarely been on health risks (Yadav and Wall 1998; Meriläinen et al. 2006).

Analyses of contaminant risks have been typically based on concepts of risks that assume objective definitions and quantifiability. This applies also to formal systems for regulation of chemicals (IPCS

1999) and pathogens (Smeets et al. 2010; WHO 2011a). Quantitative measures and models are likewise central in water economics (Harou et al. 2009; Wittver 2012). Such models are challenged, especially in complex systems, by uncertainties and ambiguities (Haag and Kaupenjohann 2001; Driedger and Eyles 2003). New frameworks, therefore, need to be developed to overcome these challenges.

The main objectives of this article are to evaluate and develop integrative frameworks for assessing health risks to water resources, particularly in the context of contamination of potable water produced by MAR. We emphasize assessment–management interfaces, socio–economic aspects of risks, and methodological issues in integration. A framework is applied to a case to build a basis for subsequent detailed analyses involving empirical data.

The structure of the remainder of the article is as follows: in “Definitions and Approaches,” we explain the definitions of key concepts and the methodological approaches used. In “Case: Potable Water Contamination Risks in a River-Based Managed Aquifer Recharge System,” we describe an illustrative case of MAR using river water, requiring an integrated risk assessment framework. In “Development of an Assessment Framework,” we develop such a framework especially for health risks from contamination of potable water based on MAR. In “Initial Application of the Assessment Framework,” we discuss key findings regarding assessment methodologies and management aspects in relation to literature, before offering summarizing conclusions and recommendations in the Discussion.

DEFINITIONS AND APPROACHES

Risk has been defined as “an uncertain consequence of an event or an activity with respect to something that humans value” (IRGC 2006). Risks are formally defined as functions of the probability and consequence of adverse events, and in the case of harmful agents as functions of their dose and response. Risks are further distinguished from hazards, defined by inherent properties of the agent without consideration of probability (IRGC 2006). In economics, risks are also defined as probabilities of opportunity loss.

Knight (1921) distinguished risk from uncertainty by defining risk as being calculable by probabilities and uncertainty as being not. This distinction is useful as there is more and better a priori information on the former. Thus, the justified level of mitigation differs: for risky events we are guided by known probabilities but for uncertain events, more caution and multifaceted reflection is justified (Morgan and Henrion 1990).

We approach human health risks of contamination of water resources and specifically in MAR from multiple perspectives based on a systems and decision analytical methodology. Our scope includes risks caused by attempts to manage risks, i.e., countervailing risks and unintended consequences, as well as offsetting benefits (Graham and Wiener 1995) and risk governance (IRGC 2006). We analyze health risks of contaminating microbes and chemicals in potable water using theoretical frameworks and conceptual models and published information on risks. We focus, instead, on reviewing methodological aspects especially in integration along multiple dimensions.

CASE: POTABLE WATER CONTAMINATION RISKS IN A RIVER-BASED MANAGED AQUIFER RECHARGE SYSTEM

Our case is the basin of River Kokemäenjoki in southwestern Finland, with several lakes that are linked with a potable water consumption area through MAR. The pretreatment process consists of flocculation and sand filtering. The pretreated river water is then infiltrated into a glaci-fluvial sand and gravel esker system (Figure 1) (Artimo et al. 2003, 2008; Kortelainen and Karhu 2009; Pugin et al. 2014). The 4 × 1 km wide water production area includes 19 infiltration basins, with a total area of ca. 2400 m2 and 13 production wells. The production started in 2011. Water flows from the infiltration areas to the production wells over the course of more than 10 weeks, which further improves the quality of the infiltrated water. The extracted water is ready for use and no other water treatment has been considered necessary. From the esker, the water flows via 60 km of spheroidal graphite cast iron pipes and is stored in large protected bedrock reservoirs before consumption in and around the city of Turku.

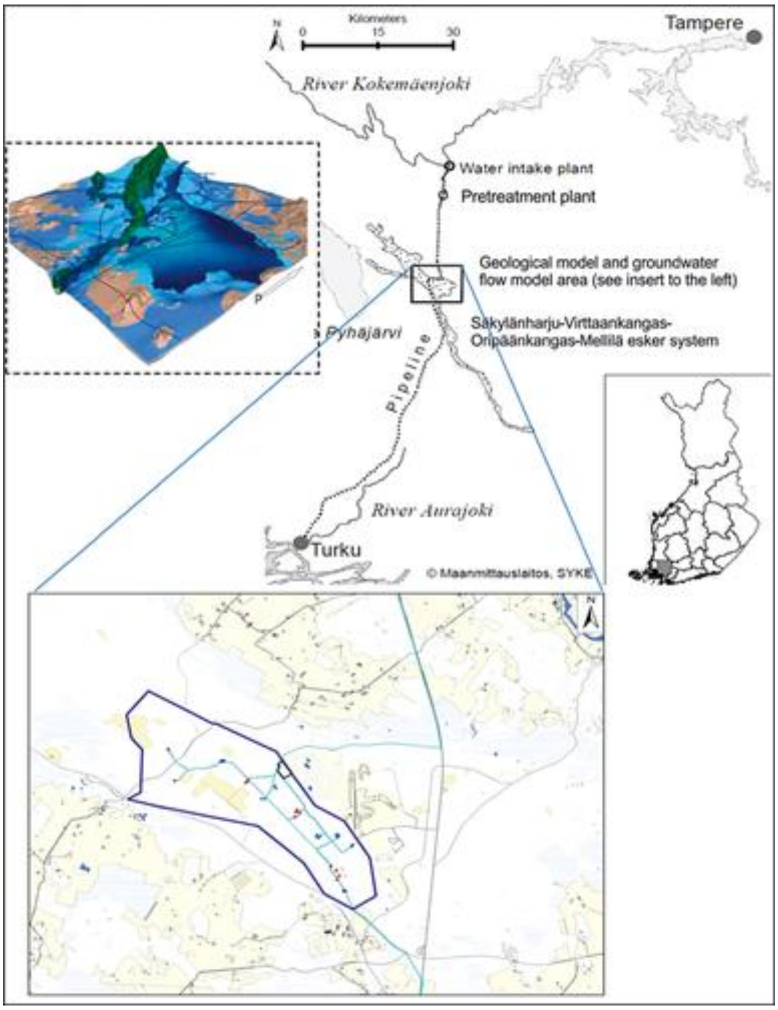

Figure 1. Map of study area, with river Kokemäenjoki and part of the lakes in its basin, water intake, and pretreatment plants, artificial groundwater recharge area in esker showing boundary (blue) of the protection area of the infiltration plant, geological, and groundwater flow model area (sand and gravel in green, groundwater and perched water aquifers blue, moraine brown), transfer pipelines to Turku region, and previous water source of Aurajoki. The geological model is from Artimo (2007).

The system of 75 000 m3 d−1 capacity has improved the potable water supply in the region, based previously on a small river of low water quality and, in some municipalities, on eutrophic lake basins. However, the long-term safety of the artificially recharged groundwater resource has caused concerns among some citizens (Lyytimäki and Assmuth 2015) possibly due to contamination sources in the upper reaches of the Kokemäki River, despite the dilution, purification, and other risk attenuation processes involved.

Some risks exceed the geographical borders of the river basin, due to administrative units and socio-economic risks at higher (regional) levels. We include the planning, construction, and projected operation period of the MAR system, also considering its previous alternatives and future options and lags in contaminants fluxes from the basin. Within this time frame, long-term (Vieno et al. 2005) and short-term variation and trends in risks may occur.

The presence of enteric pathogens and pharmaceuticals has been reported in the river (Hörman et al. 2004; Lindqvist et al. 2005), although the contaminant levels downstream may be low due also to the attenuation achieved in MAR. The contaminants enter the river from point sources such as wastewater treatment plants of upstream cities, industries, and animal shelters, and from diffuse sources such as pastures and long-range air transport. Some contamination may originate from accumulated chemicals in sediments. The assessment framework should also take into account the potential intrusion of contaminants into potable water in treatment and distribution. Accidental emissions and intentional human activities may also in principle contaminate the system despite precautions, and natural or seminatural processes such as flooding can impair the quality of the water (PIRELY 2014).

Pathogens often considered in Quantitative Microbial Risk Assessment for potable water (Hein et al. 2007; Schijven et al. 2011; Smeets 2013) in our MAR case include the enteric viruses norovirus, rotavirus, and hepatitis A virus, fecal bacteria Campylobacter spp. and Salmonella spp., environmental bacteria Legionella spp., and protozoan pathogens Giardia spp. and Cryptosporidium spp. All these have caused waterborne illness in centralized water supplies (Hrudey and Hrudey 2007; Zacheus and Miettinen 2011; Pitkänen 2013).

Among chemicals, endocrine-disrupting or hormonally active substances, pharmaceuticals, and other consumer chemicals are among primary contaminants of concern (Schwab et al. 2005; Kumar and Xagoraraki 2010; WHO 2012). These categories overlap, for example, some pharmaceuticals and other consumer chemicals have hormonal activity. The potential contaminants also include pesticides, herbicides, and other biocides. In our case, we focus on waterborne perfluorinated compounds and pharmaceuticals (Happonen 2015).

Industrial chemicals are also used in the river basin, including chemicals in the projected production of epichlorohydrin-based water-durable resin at a chemical factory complex a few km upstream from the intake plant of the aquifer recharge system, presently subject to statutory EIA procedure (PIRELY 2014). This is an example of how new facilities, agents, and factors introduce new risks, scenarios, and management needs.

Near-field activities potentially causing contamination of the esker include a golf course (nutrients and herbicides), a motor course (gasoline and additives), and a former plant school (herbicides, an example of accumulated contamination) (Joronen 2011). The chemicals that may enter the infiltration system are mainly water soluble substances sufficiently resistant to breakdown and their reaction products.

DEVELOPMENT OF AN ASSESSMENT FRAMEWORK

General aspects

For the case of potable water contamination, health risks are broken down in components along principal dimensions of risk (settings, agents, impacts, and responses), within frames specific to MAR or more general (Figure 2). Integration of these dimensions is a key task regardless of whether the perspective is qualitative, deterministic, stochastic (Bassett et al. 2012) or probabilistic (Jonsson and Johanson 2003). Operationally, tiered approaches (USEPA 2000, 2003; Rodriquez et al. 2007) proceed from qualitative risk identification to successively more detailed assessment. These aspects and approaches in the knowledge domain interact with those in the governance domain (Table 1).

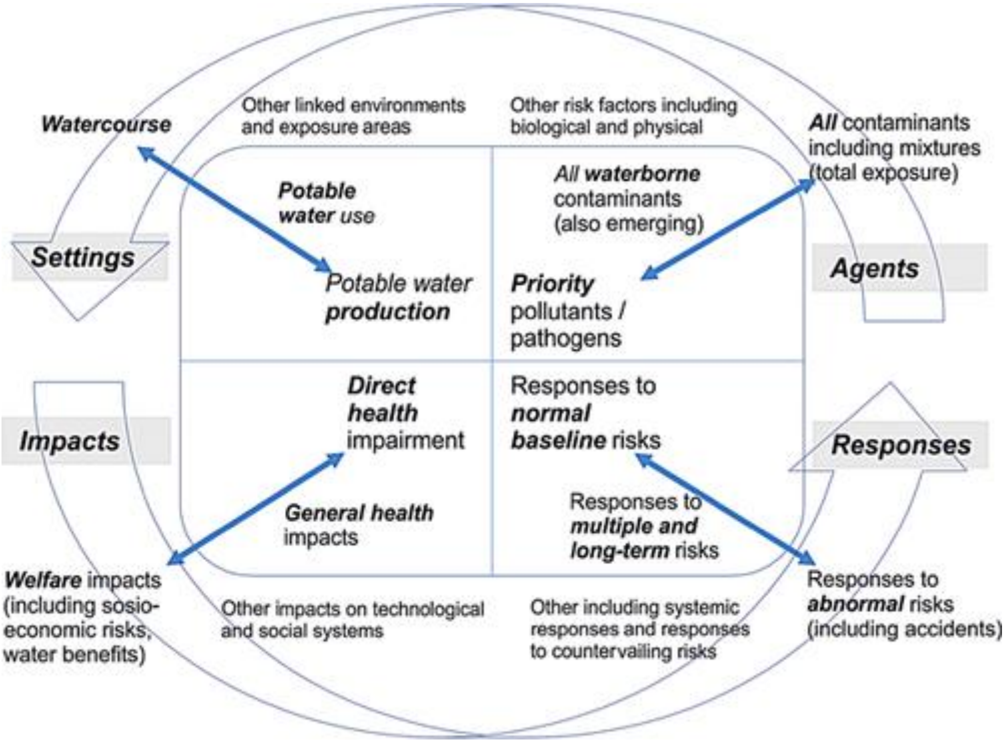

Figure 2. Solution-oriented health risk assessment on multiple levels within substantive dimensions and response categories in a case of potable water contamination. Note the shifts between basic framing (in center) and extended framing (in periphery).

Table 1. Filling gaps in areas of risk governance defined by IRGC (2009) in the case of potential health risks from MAR for potable water use

Deficit	Descriptions in MAR	Opportunities for improvement
Knowledge domain		
Early warning systems	Intake plant sensors (of proxies)	Upstream, contamination-specific
Factual knowledge	Aquifer and parts of river basin well-known; some contaminants	Generation and better use of knowledge (contaminants, drivers, cofactors)
Perception and communication	Varying opinions on recharge plant and scheme; EIA consultation; web information available	Many-sided evaluations of R/B; trust-building (with independent parties); multi-actor deliberation
Stakeholder involvement	Obligatory (plan, EIA, operation)	Up- and downstream water users
Evaluation of risk acceptability and 'risk appetite'	EIA; assumptions of net benefit and controllability	Additional discourse for collective agreements (e.g., basin and systemwide)
Misrepresentation of information (biased, selective or incomplete)	Not consciously by operators; some bias possible on all sides	Joint fact finding and evaluation; reflective representations of R/B
Understanding of complex systems, unforeseen interactions	Contaminants, fate, effects, and controls partially grasped	Extended integrated assessment linked to investigation and management
Recognition of fundamental or rapid changes (surprise events)	Partial; growing recognition of upstream releases and drivers	Foresight of out-of-the-box events (disasters, etc.) and control failures
Over- or underreliance on formal models	Hydrological, geological, and technical model focus/reliance	Dynamic, linked, multiple models (biochemical, dose/response, economic); UA
Management domain		
Responding to early warnings (cf. above)	Some systems in place within the plant (emergency response)	Notification systems (Zacheus and Miettinen 2011) (also upstream)
Designing effective risk management strategies that properly balance alternatives	Alternatives balancing in project planning on basic level	Risk-cost-benefit balancing; uncertainty management systems including distributional concerns
Considering a reasonable range of management options and their negative or positive outcomes	Basic level (e.g., additional water storage and treatment); backup sources	More extensive options analysis including consequence analysis
Designing efficient and equitable risk management policies with balanced benefits and costs	C/B distribution on standard procedures of water company	Additional consideration of R/B/C distribution policies between stakeholders (also upstream)
Implementing and enforcing decisions by will and resources	Baseline; resource needs met by pricing (within operator domain)	Extension of decision domain to upstream actors
Anticipating, monitoring and reacting to side effects of actions	Partly ad-hoc but partly advanced in planning systems	More systematic anticipation and preparedness
Reconciling time frame of risk with that of decisions and incentives	Long-term, lagged, and sudden risks may get less attention	Additional risk management systems attentive to time dimension

Deficit	Descriptions in MAR	Opportunities for improvement
Balancing transparency and confidentiality	Settled in operator domain, with confidentiality/security focus	Additional transparency for trust (e.g., EFSA guidance)
Failure to build or maintain organizational capacity	Capacity is a bit strained (e.g., by time limits and actor) involvement	Some apparently straining factors (involvement) can be turned to assets
Dealing with dispersed responsibilities for a risk's management to act cohesively	Responsibilities are concentrated, not shared (even when they could be)	Additional responsibility-sharing along risk chain and among actors
Dealing with commons problems and externalities	Standard; some can be transferred to prices	Additional policy procedures for dealing with commons issues
Managing conflicts of interests, beliefs, values and ideologies	Basic, on EIA and other regulatory and corporate policies	Additional procedures (including value discourse, also with HIA and SIA)
Acting in the face of the unexpected	Basic preparedness also on safety and contingency plans	Additional strategic horizon scanning, scenario and foresight systems

C/B = cost/benefit; EIA = Environmental Impact Assessment; EFSA = European Food Safety Agency; HIA = Health Impact Assessment; MAR = Managed Aquifer Recharge; R/B = risk/benefit; RBC = Risk/Benefit/Cost; SIA = Social Impact Assessment; UA = uncertainty analysis.

The health risks caused by contaminants to potable water supply are influenced along the chain from contaminant sources over emissions (Heberer 2002), water course fluxes (Derx et al. 2013), soil fluxes (Page, Dillon, Toze, Bixio et al. 2010), water treatment (WHO 2011b), and exposure to biological (Havelaar and Swart 2014) and socio-economic impacts. The latter are related to value chains, as many products and services are dependent on good-quality water. The risks and risk factors in these stages depend on the contaminants. Some of them are inactivated, decomposed, or removed along the chain whereas others break through or are transformed, possibly to more potent forms. The exposure routes vary (Chowdhury 2013) and so do exposed groups. Importantly, the potency and effect profile of the contaminants vary greatly.

We distinguish direct risks (e.g., from illness) and indirect risks (e.g., from lost investment; fear of infection) (Lyytimäki and Assmuth 2015). The risks can be continuous or sudden and caused by normal operations or abnormal situations (Figure 2). A distinction can also be made between risks for which there is a priori experience and other risks.

The risks are distributed within the hydrological system (including water treatment and distribution), but in socio-economic terms even broader areas require examination. With MAR using surface water, contamination risks arise along a cycle from upstream sources (point and diffuse sources) through groundwater infiltration to drinking water distribution and use. Thus, we relate the risks to the total risk of the agent or to the baseline risk for the effect (Figure 2). In broad integration, health risks need to be related to other risks, involving comparative risk–risk and risk–benefit analysis of options. For instance, whereas some solutions benefit population health, they may have countervailing risks such as formation of disinfection byproducts

(Meriläinen et al. 2006) that offset benefits. In the case of a water supply system, risks and benefits are logically compared with those in alternative or previous supplies.

In an ideal framework, all stages, scales, and aspects of the risks would be included, but in practice a more limited focus is needed, especially for detailed analysis. Most commonly, the focus in health risk assessment is on the presence and quantity of contaminants and on proxies of human exposure or on biological effects, either in surrogate animal models or in humans (Whitaker et al. 2005). Less commonly, these aspects are combined. Still less often, analyses of management are explicitly included. In the present framework, all the stages and aspects of the risk chain are included to the highest degree appropriate.

Physical, chemical, and biological aspects of risks

For assessment of the environmental transport and fate of contaminants, the simulation models SOBEK for rivers (Ropponen et al. 2013; Happonen 2015), COHERENS for lakes and estuaries (Luyten et al. 1999; Myrberg et al. 2010), INCA for basins (Whitehead et al. 1998), and MODFLOW for groundwater (McDonald and Harbaugh 2005; Hughes et al. 2014) have been selected. This selection is based on past experience, documentation, and availability of models, as well as evaluated suitability. The models are modified for the system in our case, and coupled with other models of contaminant emissions, fate, and effects, including data on physical, chemical, and biological properties of the contaminants and the influences of key environmental and technological processes and conditions (Figure 3) (Happonen 2015).

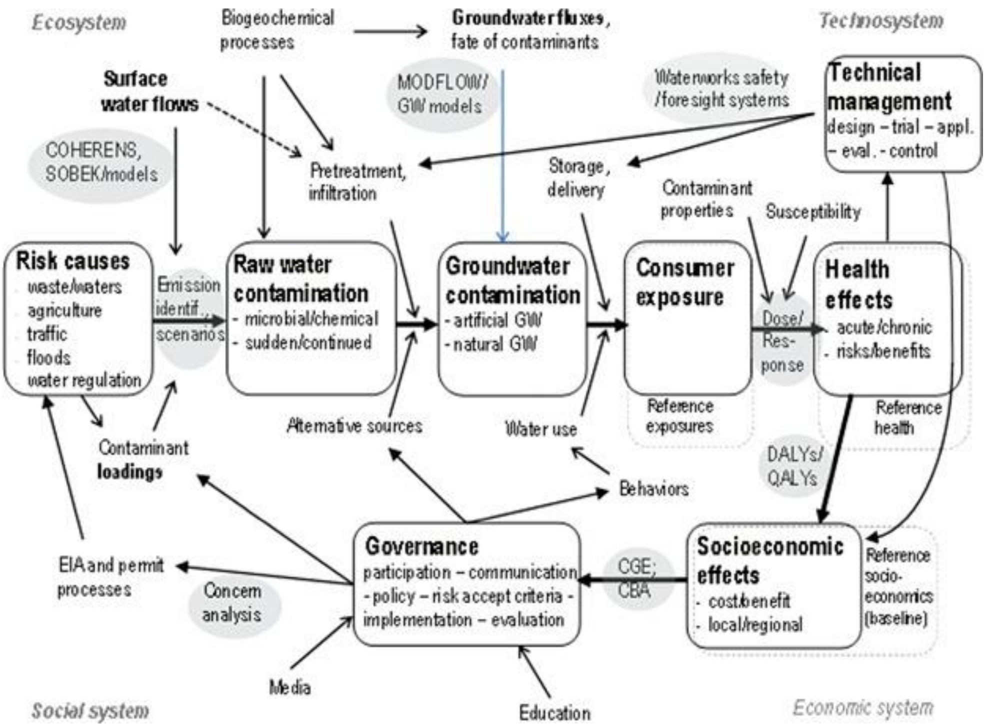

Figure 3. Metamodel of risk and impact chains in the study case, with links to physical and societal processes in responses, and key areas of analysis. Note overlaps, feedbacks, reference levels, and specific models (shown by gray shadowing). GW = groundwater; DALYs/QALYs = Disability/Quality-Adjusted Life Years; R/BA = risk/benefit analysis; CGE = Computable General Equilibrium modeling; EIA = Environmental Impact Assessment.

For the assessment of biophysical health risks, we build on standard methods of ECHA (2008), ILSI (1999), IPCS (1999, 2001), Murray et al. (2003), and the USEPA (2010, 2012, 2014) but modify them to suit our focus on contaminants in MAR (Ayuso-Gabella et al. 2011; Kumar et al. 2013). In our framework, approximations based on potency and exposure estimates can be complemented by specific models, for example, of secondary infection transmission for pathogens (Chick et al. 2001) and chronic effects of priority pollutants. On the other hand, simple metrics such as health-based guideline levels for contaminants in potable water (WHO 2011a) and aggregative Disability- or Quality-Adjusted Life-Years (DALY and QALY) (WHO 2005) are used as impact metrics (Figure 3).

Socio-economic aspects of risks

Health risks influence social and economic systems, and vice versa on many levels (Figure 3). The causes and targets of socio-economic risks and impacts vary, so that for instance the benefits from water are gained by many groups and sectors, whereas the costs of risk management can be carried by fewer actors.

The complexity of the system, the lack of data or plausible estimates on impacts, and the resultant difficulty to define model boundaries and structures constrain cost-benefit analyses, for example, regarding cobenefits, upscaling, and innovation effects. Valuation of options depend on assumptions of risk and benefit distributions and transfers (Kask and Shogren 1994). For instance, the value of cancer prevention can exceed that of microbial risk mitigation if a long latency and a high discount rate of costs are used (Alberini et al. 2006). Thus, the socio-economic impacts and aspects need to be addressed broadly, as part of risk governance where knowledge and knowledge deficiencies are included (Table 1).

We apply a regional-scale general equilibrium model VERM (Honkatukia 2013) for the socio-economic analysis. As a general equilibrium model, it accounts for the effects that common partial equilibrium analyses cannot adequately address such as full price adjustment process, industry level dependencies (among water users), demand side adjustments, and dynamic recovery processes. Computable general equilibrium (CGE) models operationalize the general equilibrium theory (Arrow and Debreu 1954; McKenzie 1954) and are commonly applied also to natural hazards and health risks (Rose and Guha 2004; Dixon et al. 2010). Although a CGE model is not sufficient for cost–benefit analysis as such, it is a good starting point because it reveals economic effects that partial equilibrium analysis will miss. Additionally, the structure of CGE models represents the national accounting system, which enables comparison with its main indicators.

We distinguish direct and indirect economic impacts. The latter are usually not as evident as the former and may not, therefore, receive appropriate attention. Direct effects include morbidity and mortality that have immediate consequences, productivity loss due to absence from work, and increased health care costs (Huovinen et al. 2013). The indirect effects are more varied. On the demand side, the commodities produced at the impacted region might lose their appeal to consumers, for example, if water quality becomes suspect. Negative demand shocks may affect water intensive commodities like food and beverages, water recreation, and water-based tourism. An example of supply side indirect effects is change in regional trade equilibrium. If the impacted area is net exporter of affected commodities, the importing regions will contract as well. If the region is net importer, the negative consequences could be alleviated by trade equilibrium adjustment. Thus the changes in regional trade equilibrium will either aggravate or attenuate the regional economic effects at national level.

Adverse effects on health are caused and also reduced by economic activities in upstream areas that are administratively unrelated to the water supply system, such as by chemical production and use or by waste (water) treatment. On the other hand, consumer health risks due to exposure of water, as well as measures taken to manage these risks, have economic impacts and risks in downstream areas, for example, costs to health care in a case of waterborne illness outbreak (Halonen et al. 2012). Further costs can be caused by lost labor and productivity in cases of illness, and by risk management measures, monitoring, administration, resource costs, and other externalities. The costs in both the water supply organization and elsewhere are influenced by the governing principles for those economic activities, also regarding how the costs can be covered and shared. Questions of water pricing, incentives for ensuring adequate infrastructure maintenance, and insurance policies may thus become relevant.

Integrated and operational framework

Based on generalized models of health risks and of risk management and the operative cycles of risk assessment and management in potable water supply (Figure 2), an integrated framework specifically for contaminants in MAR was developed (Figure 3). Some traits in the framework and the component models are generic, while there is flexibility in others, depending on the desired focus (Assmuth and Hildén 2008). This generic framework is complemented by scenarios, for example, for baseline exposures and effects and for abnormal conditions such as accidental contaminant releases and floods (Happonen 2015).

We deliberately keep the framework broad, extending it from hydro-ecological processes to health impacts and to responses in the technological and socioeconomic systems of watershed governance (Parkes et al.), while focusing on key features in the case and on the available information and analytical tools. The framework thus facilitates a chain of models, in accordance with the contamination phenomena assessed (Smith and Pollock 2012). It also considers the roles of knowledge deficits and governance deficits (Table 1).

Risk measures based on backward inference from an accepted level of adverse effect can be introduced as benchmark criteria, using models along the risk chain. For comparative purposes, margins between accepted and actual levels are used as benchmarks (Levantesi et al. 2010). In management of risks at facility level, alerts for some parts and properties of the systems are used as signals.

In traditional reliability analysis (e.g., for facility safety plans), concrete operations are in focus, usually within a well-defined engineered system (Figure 3). In our case, treatment technology includes a natural aquifer and is evaluated on an aggregate level using generalizing data from comparable systems, as the data are scarce for many technologies and contaminants, especially on long-term performance, reliability, and cost.

A complementary approach to risk is the analysis of human factors conducive to risks (IRGC 2009; Tang et al. 2013). This is justified by cases of system failures, as in the township of Nokia, Finland (in the River Kokemäenjoki area), where wastewater was accidentally led directly to the municipal water supply causing a gastro-intestinal disease outbreak (Rimhanen-Finne et al. 2010; Laine et al. 2011).

Further integrated assessment frameworks include facility-level Water Safety Plans (WHO 2005) and Environmental Impact Assessment (EIA) procedures for the infiltration plant and threatening upstream plants (Figure 3 and Table 1). Perceptions influence valuations of risks and benefits of management choices. This calls for explicit account of communication and negotiation (Russell et al. 2009). It may take place (e.g., in Social and Health Impacts Assessment) (Dreyer et al. 2010; Leppo et al. 2013), as formalized and operationalized in EIA.

INITIAL APPLICATION OF THE ASSESSMENT FRAMEWORK

Applying our framework on a qualitative level of increasing complexity and realism (Figures 2 and 3), we find that 1) framing of risks can extend beyond contaminants and factors presently measured; 2) continuous and abrupt, known and unknown risks are potentially included; 3) in each step of the chain, risks, and cofactors are identified and can be systematized by detailed models; 4) risks of microbial and chemical contamination are linked and interact with other types of risks, including technological and socio-economic; 5) some interventions give rise to subsequent risks besides intended benefits; and 6) benchmarks along the risk chain (e.g., for water quality criteria or DALYs) involve uncertainties and need also to be assessed and aligned.

The quantitative analyses so far of the contaminants and indicator substances in our case (Happonen 2015) suggest that direct health risks of the contaminants and factors considered are presently nonsignificant. However, variability and uncertainties in also these risk measures have been noted, including unknown sources of the contaminants. Moreover, other contaminants and risk factors may become important. For both extended analyses of new risk factors and in-depth analyses of presently analyzed factors, the integrated framework we present (Figure 3) helps framing and focusing.

In our case, integrated assessment and management addresses primarily the potable water transmission, production, and supply system from the river through the infiltration area to the consumption area, including treatment facilities and auxiliary systems. However, standard facility-centered safety analyses of water utilities (Westrell et al. 2003; MacGillivray et al. 2007) may also be extended to upstream operations, perhaps particularly to wastewater treatment plants and their technical and economic performance (Figure 3).

Using the categorization of risk governance deficits in knowledge and action domains (IRGC 2009), we characterize management procedures in our case and identify opportunities for development (Table 1). We identify several functioning procedures for appropriate risk governance but also development needs and opportunities. This is natural in a complex, evolving and turbulent field and in a technological solution including tensions and pressures also from concerns with health and environmental risks, and underlines the need for research and innovation.

DISCUSSION

Assessment methodologies

There is a clear need of improved methods for assessing risks from contaminants in MAR schemes, also in extended systems including river basins, aquifer and surface treatment, water distribution, and consumption areas. Many existing methodologies can be used, such as extending quantitative microbial risk assessment (Schijven et al. 2011) and aquatic risk assessment of chemicals (Hofer and Suker 2000) to include groundwater infiltration and water distribution stages, in normal and abnormal scenarios such as floods. Methods from areas such as integrated water resource modeling can also be used (Letcher et al. 2007).

Health risk assessment of waterborne contaminants has usually focused on natural scientific aspects, quantitative representations, and deterministic models (Schulman et al. 2002; Schwab et al. 2005). Simple qualitative methods for risk or hazard identification have usually been based on the notion that risks can be addressed in a rational and value-neutral manner. These approaches have also been pronounced in technical reliability analyses.

Such assessment approaches can be useful but have been shown to face important challenges. First, the complex systems and risks stretch the ability of analysts to grasp them (Briggs 2008). This is due, in part, to the connectedness (e.g., in our case, of upstream watercourse), infiltration, and treatment plant and supply network. Moreover, the complexity of subsystems in facilities and in natural systems (e.g., aquifer) limits detailed and reliable representation. Thus, there is overparametrization (Wade et al. 2008) and more generally over reliance as well as underreliance on models (Table 1). However, the complexity of the agents and factors causing risks and of the resultant impacts also plays a role, such as with heterogeneous mixtures of contaminants and with multifactorial and multi-attribute health outcomes (see knowledge deficits in Table 1).

Second, and linked to boundaries of knowledge, the framing of risks, benefits, and impacts and their natural and social contexts becomes a major issue, including the comparison of projected risks and benefits of present systems and alternative solutions. In communication between actors, reframing takes place. This requires functioning links between models in different substantive areas and geographical and time scales (Figures 1, 2, and 3). The inclusion of risk evaluation and management, although a seeming complication, can instead help to streamline assessment and to focus it on questions of most relevance. In our case, the framing needs to account for key features of the potable water supply system. Value-at-risk approaches (Yamout et al. 2007) can provide insights for risk comparisons (Havelaar et al. 2000).

Third, uncertainties are present in information on exposure and effects (Goicoechea et al. 1982; Sassi and Ruggeri 2008; Mena and Gerba 2009; Hart et al. 2013). For instance, it is common to assume contaminant concentrations in water consumed represent exposure although internal doses can be decisive. Uncertainties include distributions of risks and benefits regionally, in populations and in time, and also underlie guideline values (Ritter et al. 2007; Tardiff et al. 2009). DALYs have also been considered flawed (Anand and Hanson 1997; Østerdal 2009) due to issues in weighting, aggregation, and distribution of risks, underlining the need to unpack their foundations and uncertainties (Toze et al. 2010; Page, Dillon, Toze, Bixio et al. 2010; USEPA 2012). Sensitivity analyses (Zwietering and van Gerwen 2000) and separation of variability and uncertainty (Ragas et al. 2009) are partial answers, but uncertainties may be still better grasped by distinguishing them from ambiguity, especially in integrated models (Rotmans and Van Assselt 2001; Craye et al. 2009).

Identification of cofactors and causal relationships is crucial in all these respects. This requires conceptual models of the structures and functions of the systems and entities to be assessed. In our framework, risk, and response chains (Figure 3) help to grasp risks comprehensively.

Additional (more detailed) parts of the chains can be included, also as more information becomes available (e.g., on emissions, environmental fate, and health effects).

A key issue is the level of specificity and detail in integrated assessment, for the models to be both realistic and useful. Simple assessments can involve scenarios (USEPA 2004) and risk ranking (Kumar and Xagoraraki 2010). The need to diversify standard methods increases in detailed assessment (Notermans and Mead 1996; Zwietering 2009), requiring tailored methods (Pereira et al. 2006). Methods need to be modified to take into account particular traits and risks of the (MAR) system. For instance, mixture effects (Krishnan et al. 1997; Price et al. 2001; Assmuth, Craye et al. 2010), less-known pathogens, and risks to children require novel approaches (Maxwell et al. 2003; Murray et al. 2003; USEPA 2006). For economic aspects of risks, cost-efficiency analyses, and elicited valuations based on hypothetical (but policy or expertise based) scenarios can be used (cf., the opportunities in reducing the knowledge deficits singled out in Table 1).

Management and governance issues

In dealing with risks, there are many management and governance challenges and deficits, despite efforts to develop efficient standard approaches (CAC 2007; Hochstrat et al. 2010). This is particularly the case with complex and contested risks related to health concerns (Assmuth, Hildén et al. 2010). IRGC (2009) has systematized and extensively described these deficits within management and related knowledge realms. We use this categorization of deficits as a basis for a synthesizing evaluation of risk management needs and opportunities in the present case (Table 1), noting that questions of knowledge and assessment interact with those of management and policy (Heinz et al. 2007).

We can discern several functioning systems for managing risks also from contamination in the present case. Some of these systems and approaches are inherent in the type of water supply implemented, have a statutory or regulatory basis, and are explicitly formulated, operationalized and documented (e.g., based on the regulatory permit of the MAR system), whereas others are an implicit part of normal strategies and operations, and still others are in a rudimentary stage of development. We can thus note needs and opportunities for dealing with risks more extensively, both in terms of agents, pathways, factors and impacts, and regarding the distribution of risks spatially, in time and among populations and actors (Table 1). Such extensions can be linked with watershed governance (Parkes et al.) encompassing more numerous compartments and aspects of risks and impacts.

Benefits from management are hoped to overcompensate for health risks and the economic losses they incur. The present case of MAR is generally considered an improvement over the previous water supply in the Turku region. This was, indeed, a key argument for the present scheme. Investments in it might indeed have reduced, even cost-efficiently minimized, the total waterborne health risks. Also in the present system, additional upgrades are conceivable (e.g., to deal with emerging future risks), but considerations of capacity, reliability, and robustness, and the long-term balance of risks and benefits might tip the scales in favor of the present system instead of further up-grade.

Risk management approaches need to be fit to purpose, flexible but robust, transparent and participatory (to the extent appropriate), efficient and equitable, part of normal managerial and operative culture, and thus not addressing specific risks of contaminants too separately from overall management. Simple approaches are needed in practice, such as decision criteria based on guideline values and other proxies (Figure 3). The emphasis on improvement opportunities does not imply that all of them would need to be taken on at least immediately and in a similar way. Improvements depend on collaboration and coordination possibilities and can be seen as long-term goals in an institutional and social learning process. Many of the deficits and gaps can be filled by developing and implementing contamination-focused but also comprehensive risk analytical and risk management elements in Water Safety Plans (Smeets et al. 2010), river basin management plans (Volk et al. 2009), and other such procedures.

Specifically, participatory and deliberative approaches, co-constitution of knowledge and conduct of assessments by several actors, not only administrative sectors (Jalba et al. 2010) can add to traditional expert analyses, in a process of social learning (Ison et al. 2007). This is especially true in contested risk and impact assessment cases, and in risk questions that are more based on value judgments and policies than on objective facts, such as acceptable levels of precaution (Illing 1999; Hrudey and Leiss 2003). These need to be linked with economic and technical aspects of risks and impacts (Bohnenblust and Slovic 1998). Deliberation is also needed between experts in different areas, between experts (modelers) and managers or regulatory authorities, and between these and other stakeholders (Shepherd et al. 2006). Thus, attention is needed to participation and communication in adaptive governance in all types of assessment (Baggett et al. 2006; Pahl-Wostl 2007). Such participation is evolving both among professionals and other actors. Partly regardless of projected, estimated, and also verified or demonstrated impacts, in our case actors may perceive and evaluate risks from very different viewpoints (Lyytimäki and Assmuth 2015).

CONCLUSIONS

The following conclusions and recommendations can be offered:

Our analysis of the extensive MAR case showed the importance of addressing risks broadly, including technological and socio-economic aspects, and in relation to other risks and to benefits of alternatives. The integrative approach helps to find a suitable focus for specific analyses, in both initial scoping and subsequent generalization and contextualization.

Based on the framework presented here, an example chain of models was evaluated for the detailed analysis of risks from contaminants in a water supply system (Figure 3). Our examination showed that it is useful to structure assessment along chains of risk formation and responses, in particular to account for cofactors, scales, and dynamics of risks.

The integrated multimethod approach applied posed challenges for linking information in different areas, but helped to make them more relevant for risk management. In general, an iterative, reflective or heuristic methodology was found feasible, coupled with uncertainty assessment and management (Figures 2 and 3).

We noted the need to balance generality and specificity both in the scope of the assessment and regarding the simplification and detail, such as when selecting specific contaminants for further analysis. The integrated model (Figure 3) was shown to help in finding this balance.

We found that, even though improvements in health risk can be achieved by MAR over the baseline risk in the previous low-quality water supply, new and unexpected risks and impacts can arise. Therefore, risk management systems should include specific processes of development for which an integrated assessment management model is important (Table 1).

Acknowledgment

Funding for this work has been received from Academy of Finland on the CONPAT project (Pathways, risks and management of aquatic contaminants) of the AKVA program. The work is also based indirectly on other projects, including the NoMiracle project of the 6th Framework Programme for R&D of the European Union, and the Finnish Fulbright Center on a grant to the lead author to Tufts University. Valuable comments on a draft have been provided by Dr. I. Miettinen and Dr. J. Tuomisto in THL, and A. Artimo, S. Saraperä, and O. Puurunen in Turku Region Water Company who have kindly provided map materials. The authors are solely responsible for the views presented.

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