Contaminants and pathogens in waterways - economic assessment of risks

Simola, Antti*[1], Juntunen, Janne†[2], and Meriläinen, Päivi‡[3]

[1]VATT Institute for Economic Research
[2]Finnish Environment Institute
[3]National Institute for Health and Welfare

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Abstract

We have studied economic effects of harmful substance emissions to waterways. In order to build a plausible framework of events, we employed four separate models from different fields of study. First, two models of physical environment, which track the movement of harmful substances in lakes and rivers, respectively, from sources to the end users. Second, a statistical QMRA analysis, which assesses the public health risks. Finally, a regional CGE model that we used for assessing the economic effects.

In order to substantiate our analysis, we used an illustrative case of a recently built artificial recharge system in Southern Finland that provides water for a 300 000 inhabitant area, which includes a 180 000 inhabitant urban center, Turku. We examine the effects of various chemicals and microbes separately. Our economic calculations allow for direct effects on labor productivity, increases in health care expenditures and indirect effects for local businesses. The modeling technique incorporates economic adjustment between industries and regions on monthly basis.

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*antti.simola@vatt.fi
†janne.juntunen@syke.fi
‡paivi.merilainen@thl.fi

We found that only an extreme hazard is notable threat to public health and has small, measurable economic consequences. The epidemic is likely to spread widely in the urban setting we examined, but is also short lived in both public health and economic terms. Due to intra- and interregional adjustment, the total effect is smaller than the direct loss of labor productivity. The major remaining uncertainty in economic assessment are the indirect effects. However, we consider our results relatively robust.

1 Introduction

Contaminants and pathogens are likely to cause harm to human health if they end up in potable water. Although the adverse health effects are already unpleasant to the affected individuals themselves, they also have more widely ranging negative effects to the rest of the society. Although substantiating the total effects is surely a daunting task, we can make a headway by proxying the economic consequences. The economic consequences of water quality, or lack thereof, have been duly recognized. In some developing countries lack of pure water is a major hindrance for economic growth [1] and OECD has predicted that in 2030 over half of the world's population will be living with water scarcity. [11]

At the same time publicly provided pure water has become a norm in the industrialized countries. Nevertheless, the means of delivering the water varies, and in cases of low probability hazards the harmful substances can spread widely in short time and affect notable share of citizens. Customs of using water vary between industrialized countries. Some countries enjoy water resources of such high quality that direct consumption from tap is common. Consequently such countries might be more vulnerable for sudden and unexpected water quality deterioration. Nowadays ever increasing array of chemicals is applied in manufacturing processes, which also adds to potential water related hazards. At the same time the risk for sabotage has become evident as well. The pathogens are generally less prevalent than in the developing countries, but their dispersion through waterways needs to be prevented with appropriate water treatment measures. Although new technologies have created new water related health risks, they have also improved the ways the risks can be mitigated. Functioning waterworks usually demand reallocation of public resources, which makes it an area prone to inefficiencies and corruption.

It is nevertheless challenging to match the costs and benefits of mitigation of the risks because the probabilities and the valuation of safety are hard to measure. The costs themselves are relatively straightforward to take into account as they include investment and operation costs of prevention measures that are calculable given existing data. The accounting of benefits poses bigger challenges. First, the risk of a particular hazard has uncertainty in Knightian [9] terms rather than mere risk.Thus, it is difficult to determine how frequently a relevant hazard takes place as the data on previous events might not be a reliable guide. [1] Second, the subjective valuation of safety should be taken into account. If consumers value safety for itself, they are willing to pay for higher level of water safety than the consequent avoided risk would dictate. In economic theory such behavior is known as risk aversion. Barro [2] showed that a substantial environmental investment can be justified with reasonable calibration of risk aversion without needing to "invoke unrealistically low rate of time preference".

The aforementioned difficulties withstanding, we can nevertheless make the uncertainties more explicit and therefore frame the needed decisions more accurately. In this study we do just that by using various modeling techniques. Our work will help to frame similar problems more clearly although precise recommendations will depend more on particularities such as local conditions.

Next section 2 more explicitly presents the methods we applied. The following section 3 gathers the main results from each stage of the work, and the following 4 analyzes the results. Finally, the last chapter 5 discusses the results and concludes the work.

2 Material and Methods

2.1 Chain of Models

In order to comprehensively assess the problem, we have applied a chain of four models, which each represents a particular stage of events. At the first stage, we use computable models of physical environment and water flows to predict how the harmful substances eddy from potential source of hazard to the consumers. The second stage takes on the change in end-users' exposure to the harmful substances and predicts the consequent health effects. The

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[1] Knight distinguished risk and uncertainty; the former can be assigned a mathematical probability whereas the latter cannot. Modern version of risk and uncertainty dichotomy is labeled as black swan phenomenon; a low probability event that has a high impact. In other words the phenomenon obeys a probability distribution that is fat-tailed.

final stage takes on the health effects and interprets them in economic terms. The following subsections give more detail on each modeling step.

Water transport modeling

Watercourses of the study area contains three lakes namely Pyhäjärvi, Kulovesi and Rautavesi, and River Kokemäenjoki. We use computational models that utilize both approximations described above. The Lake Pyhäjärvi is modeled by 3D Coherens model [12] that use Boussinesq approximation when solving the Navier-Stokes equation and River Kokemäenjoki (Kulovesi and Rautavesi included) is modeled by Sobek [3] that solves one-dimensional (1-D) Saint-Venant equation. [2]

In both models the municipal and industrial water treatment plants located on the study area are treated as sources. Incoming water amounts are obtained from these sources with varying accuracy but the concentrations of studied chemical compounds and microbes are determined four times per year (3 month interval). Studied chemicals (PFOA, Acesulfame-K) are stable but both studied microbes (E. coli and Norovirus GII) are dying organisms and this process is taken into account when considering dispersion of them in water bodies. In both cases decaying is assumed to be exponential and decay rates are calculated from survival experiments performed by the National Institute for Health and Welfare (THL). Since it is well known that both radiation and temperature affect dying, they have been performed in dark and light, and in cold (5^oC) and warm (15^oC) conditions. In real environmental conditions both are subject to changes. Based on calculated decay rates linear regression is applied in order to approximate the decay rates in the conditions not measured. Coherens model calculates the incoming amount of solar radiation (taking into account cloudiness) with an assumption that solar radiation of $600W/m^2$ corresponds to a lighted environment and $0W/m^2$ to dark one. Linear regression was applied in this interval. In SOBEK model we used time-independent decay rate, since the model does not apply environmental forcing.

Detailed description of actual SOBEK model application for the River Kokemäenjoki can be found from Happonen et al. (2016) [7]. Only major difference is that the work and results presented here is based on SOBEK model that use as boundary concentration provided by Coherens application.

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[2] See appendix A for more detailed description of water models.

QMRA analysis

After the transport modeling stage we assessed human health effects by quantitative microbial risk assessment (QMRA) (Haas et al., 1999 [6]; WHO 2004 [10]). QMRA method has been previously used for microbial contamination in food and water and in this study we apply it to comparative assessment of health effects from water resources to consumer tap.

In the QMRA assessment we selected a number of different contamination scenarios for different pathogen levels in raw and drinking water to investigate the effectiveness of the water treatment process regards to health effects caused by pathogenic microbes. Contamination scenarios assessed are described in subsection 2.2. The microbes selected in the assessment were campylobacter, salmonella, noroviruses GI and GII, and adenovirus, which all cause diarrheal diseases when ingested via drinking water.

In exposure assessment we assumed that a person drinking contaminated tap water can be infected only once due to the pathogens and that the person will not infect others. The only health effect assessed here was diarrhea and age distribution was not taken into account.

Health effects of microbial contamination in drinking water were assessed by combining the pathogenic levels in river water from microbial water analysis and transport models, removal efficiency of the water treatment process (pre-treatment, artificial groundwater production, chlorination), consumer exposure to drinking water by oral exposure, dose responses of microbes and probability of illness from infection.

Regional economic modeling

At the final stage we calculate the economic effects, which derive from the adverse health effects assessed in the previous stage. We use open data to interpret the illness probabilities as changes in labor productivity. The data includes population in affected municipalities by age categories and labor market statuses. We constructed a stochastic simulation model that gives an estimate of the mean labor productivity change and its variation. The model differentiates the illnesses caused by particular microbes by their duration.

We employed the productivity changes in a single country multi-regional computable general equilibrium (CGE) model. The model descends from TERM, The Enormous Regional Model, which was first applied in the analysis of Australian drought. [8]. That study effectively displayed the strengths of a CGE model over more traditional input/output and partial equilibrium

(PE) models in regional economic issues. First, in CGE models the adjustment processes between industries and regions are more realistic than in the other types of models. That ensures that the effects are kept in perspective. Second, the PE models by definition lack the ability to account for the effects to the whole economy. The CGE models are therefore more capable to evaluate the investment costs of various water treatment technologies against the achieved benefits.

It is convenient to classify the economic effects as direct or indirect depending on how they relate to the actual epidemic. [3] We consider one direct effect, which is the reduction in labor productivity due to workers' absenteeism related to their own and their children's illnesses. Here we assume that employers are bound by their contracts and need to pay wages fully for each sick leave day, which is a reasonable assumption for our study area. The rest of the economic effects are indirect in the sense that they do not result directly from the illness, but via some other factor. First, the health care expenses are likely to rise in case of a widespread epidemic and thus divert resources from the equilibrium state. Second, the affected area could face reduced demand for its water related commodities if it is perceived that they might contain some risk themselves. Tourism activities, manufacturing of food and beverages, recreational services are all examples of such commodities. These kind of losses that are based on subjective and perhaps irrational fears might actually be more important and long-lasting than the actual direct effects. For instance Dixon et al. [4] concluded that in a hypothetical H1N1 swine flu case in US, the indirect demand losses were the biggest factor in accumulated loss. Last, the affected population might adjust its consumption at least during the epidemic by reducing consumption of some commodities like leisure time activities.

We measured the economic effects at both regional and national levels by deviating a national baseline scenario with the aforementioned direct and indirect economic effects at our study region. The baseline rest on a national level long-term economic forecast, which is also derived with a CGE model. The model has recursive dynamics with monthly time periods, which allows us to model the effects of a short time epidemic more accurately than a typical yearly based CGE model would do. In general the monthly make-up

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[3] Another way to classify economic effects is to consider income cost and intrinsic cost. The income cost is simply the foregone income. The intrinsic cost is the value of prematurely lost lives and illness suffered. Fan et al. [5] found that the more severe the epidemic is, the higher the share of intrinsic costs is in the total effects. In our work we consider only the income cost because the intrinsic cost is harder to measure and also very unlikely to be prominent in our case as diarrheal mortality is low in our study area.

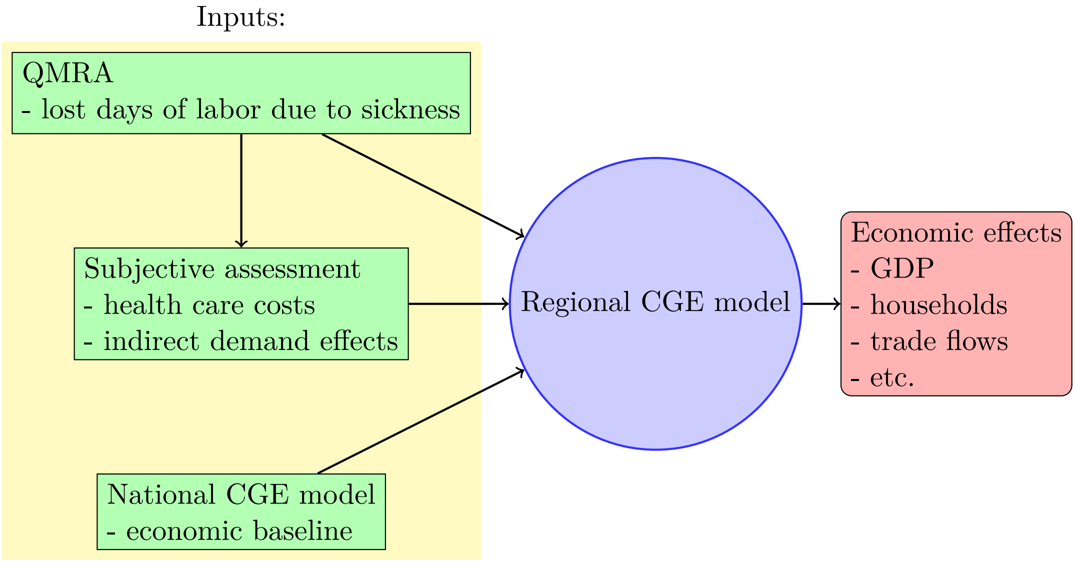

Figure 1: Inputs and outputs in economic model stage.

implies less room for adjustment and requires larger one-time shocks than in a yearly make-up. As regions vary in their industrial composition and trade relations, they might be affected unequally as some regions have more to lose than others. Our model includes these aspects by default. Figure 1 summarizes the inputs and outputs of this stage.

2.2 Scenarios

Water course prior to the artificial recharge system carries municipal waste water with microbial and chemical contaminants that can pose a risk to human health. We used few scenarios in order to compare various contamination situations from flood to operational malfunction. The scenarios we include here are:

1. Flood and heavy rain
2. Draught
3. Process failure in pre-treatment phase
4. Wastewater spill

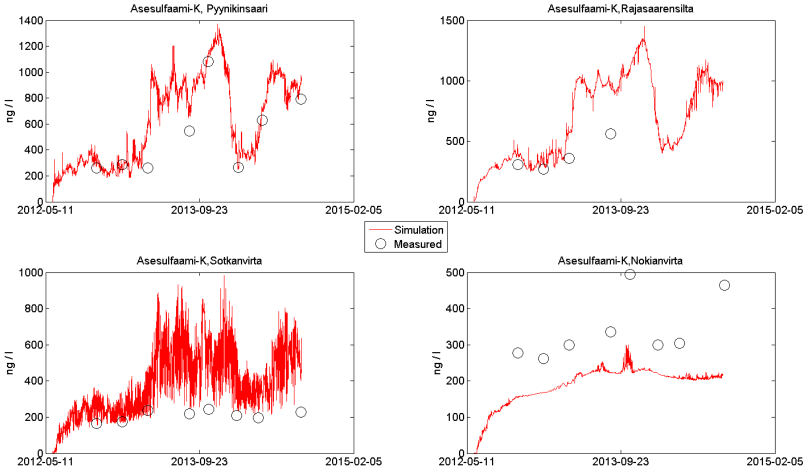

Figure 2: Comparison of simulated and measured Acesulfame-K concentration at selected sites at lake Pyhäjärvi

3 Results

3.1 Contaminants and pathogens drift in waterways

Uncertainty of numerical models can be high if no calibration is performed. We calibrate the SOBEK model to the water heights along the river but the hydrodynamics part of Coherens application itself is not calibrated. However parameterization of underlying Coherens application is same that is found reasonable for other lakes and it is expected to represent the real dynamics. In fact dispersion studies of stable chemical Acesulfame-K can be interpreted to be calibration of underlying chain of transport models.

Figure 2 illustrates the water transport models. It presents simulated and measured Acesulfame-K concentrations in four different locations. Subfigure 2a presents concentration at the nearest measuring site of the largest municipal waste water treatment plant of the study area. Subfigure 2d presents concentrations at the mouth of River Kokemäenjoki. This concentration is actually the one that is used as the open boundary value at the SOBEK river model.

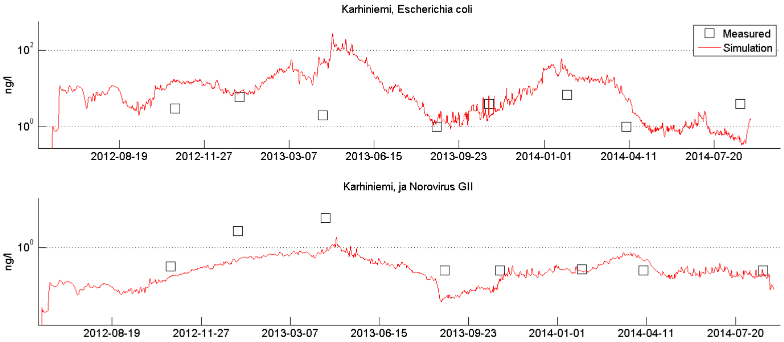

Figure 3: Comparison of simulated and measured concentration of microbes at Karhiniemi

3.2 Health risk assessment

Health risk assessment by QMRA revealed that only the most severe scenario, the wastewater spill at the artificial recharge plant, caused notable health effects in the population. Figure 4 shows the daily illnesses during an outbreak for all the scenarios.

This result can be explained by the efficiency of current water treatment processes. Additionally, multiple steps in the process ensure that only a sequence of low probability events will lead to realization of the scenarios. In the wastewater spill scenario there are no treatment steps after contamination and before consumption. Consequently, only that scenario proved to have notable effects and thus we concentrate in economic calculations to that extreme scenario only.

The highest probability of infection in the most severe case is with noroviruses resulting up to 200 and 150 cases of illnesses in the exposed population for GI and GII forms, respectively. Most likely cases for diarrheal diseases are normally due to virus infections, especially norovirus in Nordic countries.

3.3 Regional economic effects

We apply the previous section's results for the wastewater spill scenario in order to calculate the economic effects. First, we approximate the exogenous decrease in labor productivity as $labProd = employed_{ill}/employed_{tot} * \frac{1}{30}$, where $employed_{ill}$ is the affected employed population and $employed_{tot}$ is the total employed population of the region. Denominator 30 reconciles

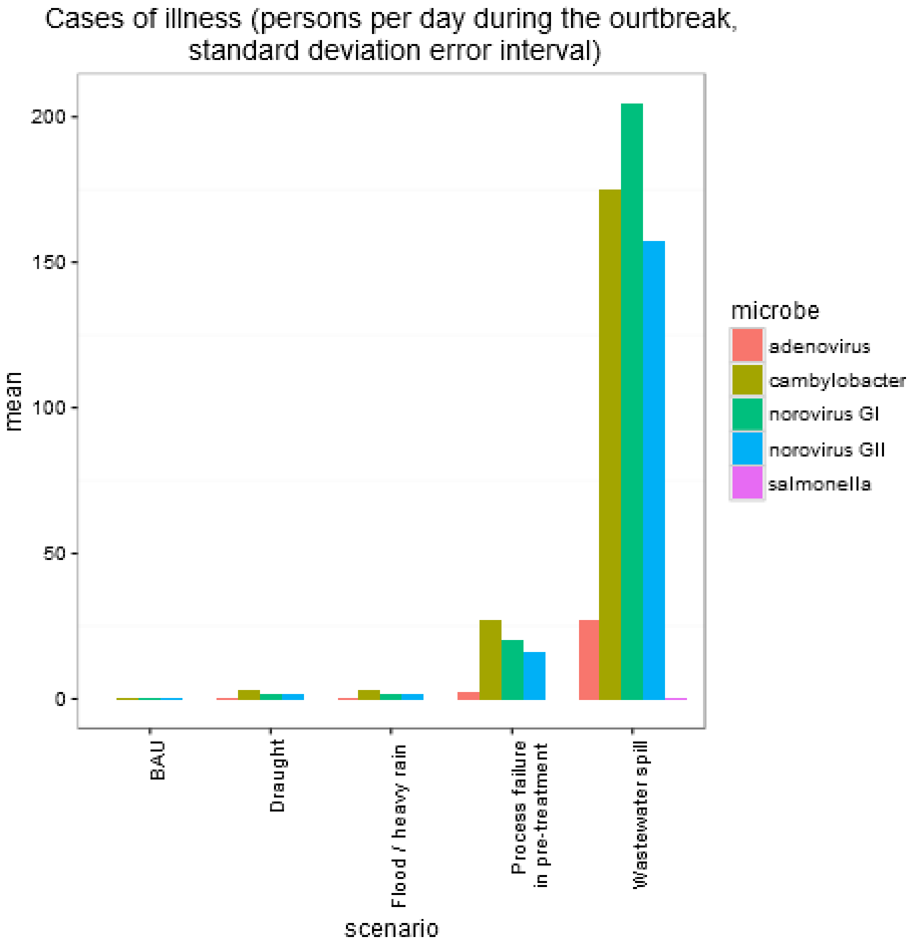

Figure 4: Cases of diarrhea illness due to exposure to microbial contamination of drinking water for different contamination scenarios.

daily illness estimates to the required monthly time frame of our model. We estimated $employed_{ill}$ with a stochastic simulation model. First, each person is sampled a labor market status, either employed or outside labor force, based on municipality level data, which gives us probability of being in labor force based on age. [4] Then a health status for each person in the

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[4] The population data has yearly age structure for each municipality, whereas the employment data has only ten years age brackets for each municipality. We applied cubic spline smoothing to the employment data in order to have more realistic employment rates per age. Both data are for year 2013, which is the newest that is available for both.

affected municipalities: person is either healthy or affected with an illness that has mean duration with Poisson process (see Table 1 for applied values).

pathogen	Poisson λ
adenovirus	4
cambylobacter	4
norovirus GI	2
norovirus GII	2
salmonella	5

Table 1: Applied mean illness durations.

In the following periods new health status is sampled for the healthy persons. After recovering from an illness, the person returns to healthy population and is again subject to sampling of an updated health status. In order to account for parents staying home because of affected children, each child under age of ten is sampled a probability of parents' labor market and health statuses. The process is iterated for the pre-determined duration of the outbreak. In the end the number of illnesses of adults in labor markets and number of illnesses of children whose parents are in labor force and not themselves affected by the illness are summed together, which is our estimate for $employed_{ill}$. Figure 5 presents the distribution of $employed_{ill}$ for a wastewater spill that lasts ten days. The distribution has mean value -0.34%, which we apply in simulations.

Due to lack of empirical analysis on the indirect effects, we resort to Fermi estimation. We assume that the indirect effects are proportional to the labor productivity decrease. In order to approximate the changes in health care expenses we set the lower bound to zero (no changes) and the upper bound equal to $labProd$. We use the midpoint $labProd/2$ as the default guess.

We assume that the indirect demand decreases by $2 * labProd$ during the first period and gradually returns to the baseline during next five months. The decrease in demand for recreational services we set equal to $labProd$ in the first period only after which it returns to the baseline level.

Figure 6 shows the changes in regional GDPs due to epidemic. The bars display each separate region while the line sums the total national effects. The affected region expectedly garners some economic losses although less than the direct effect of labor productivity decrease. In general this is explained by the intra- and interregional adjustment. The other regions are able to gain albeit marginally, which alleviates the national effects some-

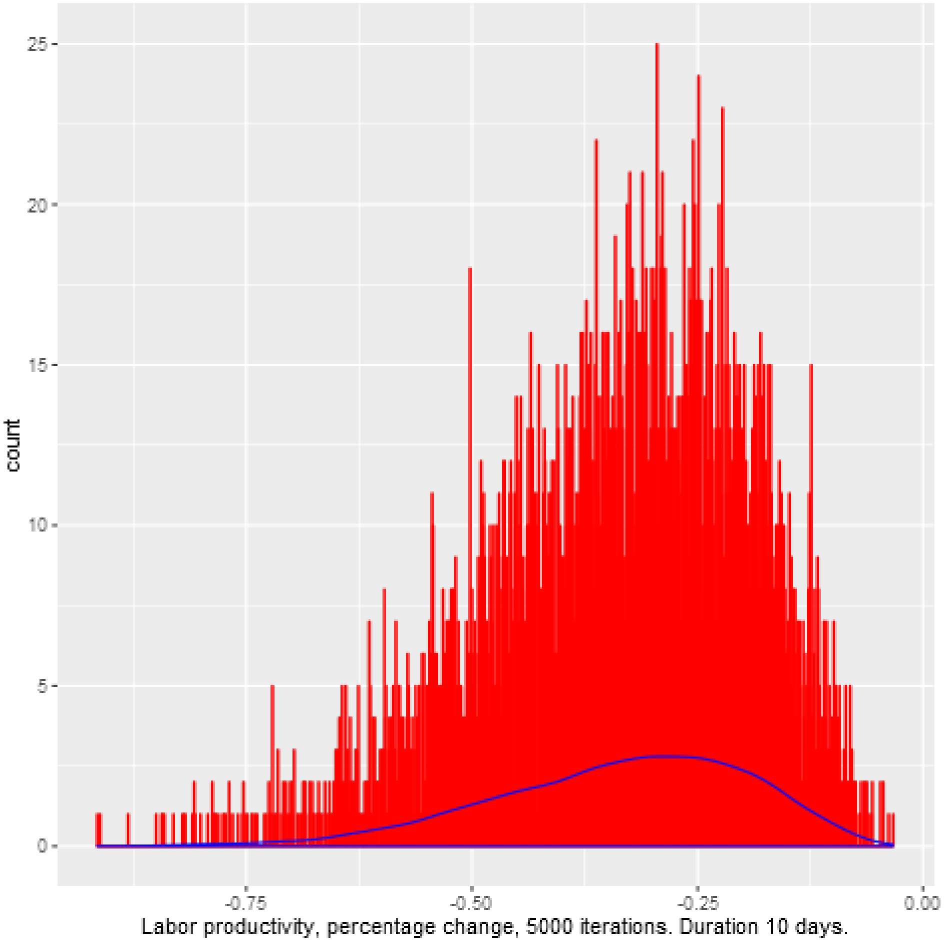

Figure 5: Monthly change in labor productivity due to wastewater spill.

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Figure 7 depicts the total GDP change decomposed to direct and indirect effects. We see that the direct effects forms the bulk of the total immediate effects. Indirect demand effect are important especially after the direct effects have subsided. In sum the total effects are cumulatively 1.5 times larger than the initial direct effects. Therefore calculations that only include lost workdays miss some of the total effects.

Figure 8 depicts changes in households disposable incomes. We can see that the households are more severely affected than the rest of the economy as the public sector actually increases its consumption when the health care

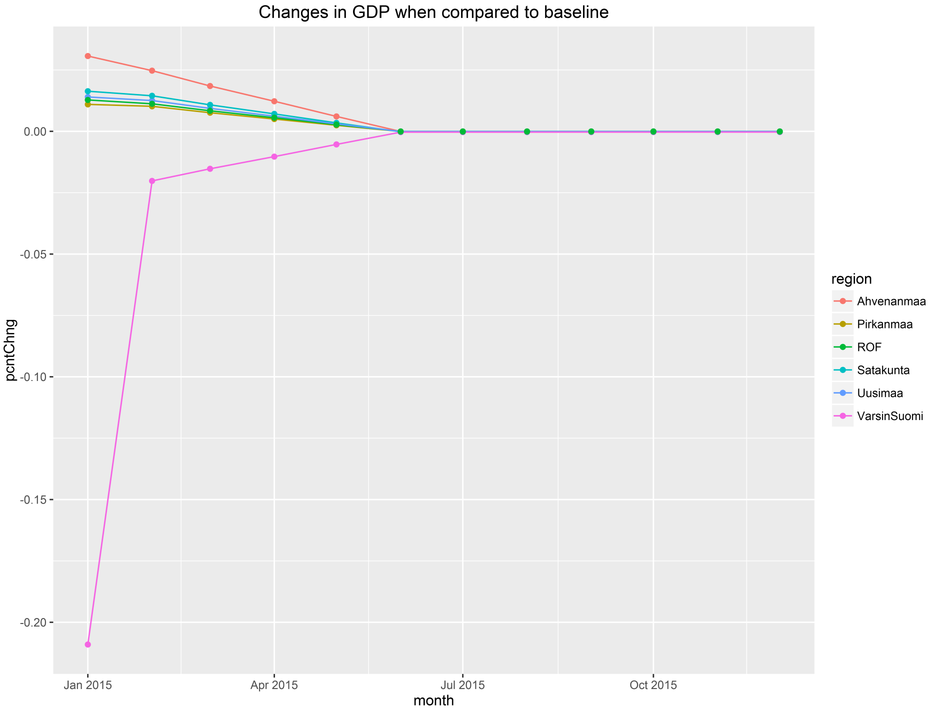

Figure 6: Changes in regional GDPs - cumulative percentage change in comparison to baseline.

expenses increase due to epidemic. Thus, the change in the households' disposable income is perhaps better indicator of the welfare effects than GDP.The effects in the affected region are compensated by increased incomes in the other regions.

Figure 9 depicts the changes in real wages, which reveals that although the other regions temporarily gain market expansion, they are nevertheless less well off as well due to overall price level increase.

4 Analysis

Our study has showed that although there are many potential risks related to water treatment, only few have notable effects on human health and economy. In our analysis only one scenario contained such a risk. This information is useful for the planners of municipal water treatment and distribution as it helps to target the most likely hazards.

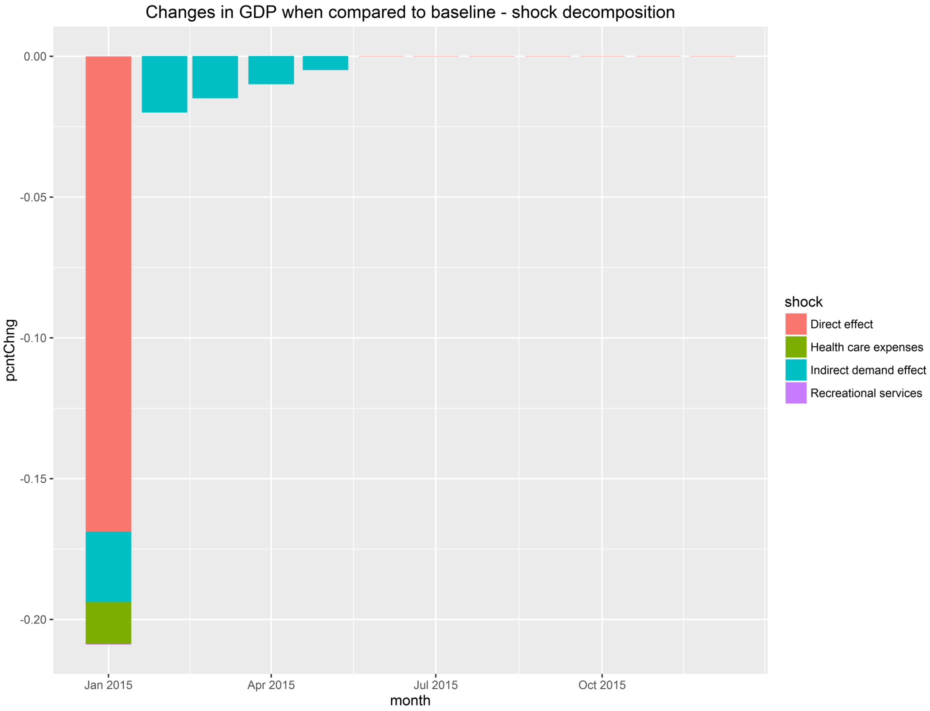

Figure 7: Changes in regional GDPs - cumulative percentage change in comparison to baseline.

Moreover, there are indirect economic effects that should be taken into account and the actual economic loss is 1.5 times larger than the initial productivity loss. Furthermore, the households' disposable income decreases more, which indicates more severe welfare loss. The affected region is more severely hit while other regions marginally gain. This is conditional on the affected region's internal trade position. The overall decrease in real wages also indicates that the gains in other regions come at a cost.

5 Discussion

In this study we have suggested one way for economically quantify environmentally transported hazards that have effects on human health. Such an analysis has potentially several policy relevant applications. We see this as a good starting point for similar analyses. However, we had to omit a few factors that could be considered in subsequent applications. Our analysis

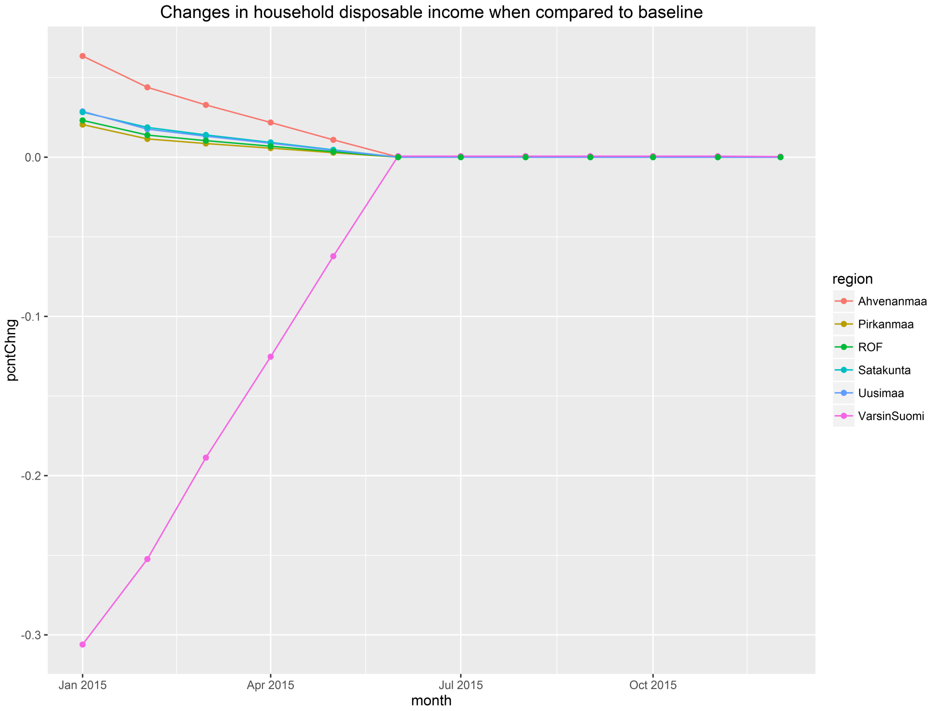

Figure 8: Changes in regional households' disposable incomes - cumulative percentage change in comparison to baseline.

concentrates on treatment of drinking water and we thus omit problems caused by e.g. contaminated swimming waters, which is a less controllable issue.

The economic analysis is not complete either as it is still restricted to a single event. Proper cost-benefit analysis would require assessment of long term probabilities of adverse effects and integration of risk-aversion to the analysis.

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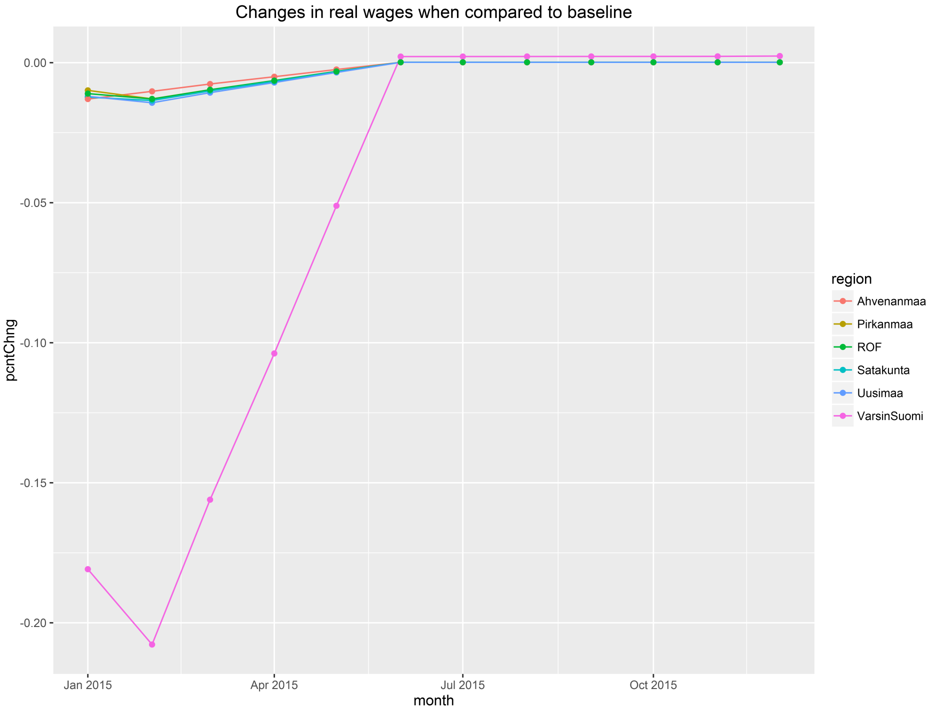

Figure 9: Changes in regional real wages - cumulative percentage change in comparison to baseline.

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Appendices

A Theoretical description of water models

Theoretical description for the transport of harmful substances in a aquatic environment is provided by advection-diffusion equation

$$\frac{\partial c}{\partial t} = \nabla \cdot (D\nabla c) - \nabla \cdot (\vec{v}c) + R, \tag{1}$$

where c is conservation of studied substance, D is diffusion coefficient, $\vec{v}$ is the fluid velocity and R represent the possible sinks and sources. In practical applications diffusion coefficient D and fluid velocities $\vec{v}$ depends of time and locations. In order to solve equation 1one must know the diffusion and velocities. This is achieved by solving the Navier-Stokes equation

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{U} + \vec{g}, \tag{2}$$

where $\vec{U} = u\hat{\mathrm{i}} + v\hat{\mathrm{j}} + w\hat{\mathrm{k}}$ is flow velocity, ρ is density, μ is viscosity and $\vec{g}$ represents a body forces. In most application $\vec{g}$ = gravity. In general form it is even today quite impossible to solve full Navier-Stokes equation at least when considering simulations concerning real lakes and rivers with time dependent meteorological forcing etc. Therefore reasonable approximation to the "full" Navier-Stokes equation are usually made in order to solve them. Suitable approximations depend on the characteristic flow environment and physics that is assumed to be important. In most cases lakes are modelled using Boussinesq approximation and rivers by (1-D) Saint-Venant equation i.e., utilizing shallow water approximation. In Boussinesq approximation density differences are ignored if they do not appear as a multiplier of gravity. Fundamental assumption is basically that the difference in inertia is negligible but gravity is sufficiently strong to make the specific weight appreciably different between the two fluids. In shallow water approximation that leads to one-dimensional (1-D) Saint-Venant equation when they are simplified enough fundamental assumption is that vertical length scale is much smaller than horizontal ones. In addition since shallow water approximation beginnings by depth integrating Navier-Stokes equation it leads equations that describe totally mixes water bodies, in other words are unable to describe processes that take place in vertical direction.