Human health impact of chemical contaminants in drinking water – usefulness of the DALY concept

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Summary

Health loss due to exposure to contaminants through the environment, workplace, food or drinking water factor may be predicted by a health impact assessment. The health impact may be expressed in disability adjusted life years (DALYs), which facilitates the comparison between health effects due to different types of risks by taking into account severity and duration of the effects. This report gives an introduction on the DALY-concept, describes several examples and discusses the usefulness of this method in human health impact assessment of exposure to drinking water contaminants. Among the Dutch population, the total health loss due to disease amounts 273,000 DALYs per million persons per year. Of this total burden of disease, roughly 5% may be attributed to nine environmental factors and roughly 1% to occupational exposure to chemical agents.

In this report we present a general methodology to estimate human health loss caused by exposure to drinking water contaminants. To illustrate this methodology, we performed a case study on a theoretical exposure to seven genotoxic compounds at guideline values. We estimated the total health loss from a theoretical lifelong exposure to the selected compounds through drinking water at 0.02 to 3 DALYs per million persons per year. This case study shows that the theoretical health loss by drinking water contaminants is very low compared to exposure to (geno)toxic compounds through other routes e.g. the environment. In the Dutch drinking water, however, concentrations of the selected genotoxic contaminants are generally lower than the guideline value which implicates that we here make an overestimation of the potential health impact.

Many studies emphasize the valuable use of DALYs to express the burden of disease or health loss by a specific factor. The application of DALYs in health impact assessment of exposure to drinking water contaminants is generally limited to genotoxic compounds. For non-genotoxic carcinogens and other toxicants with a threshold effect no health effects are expected below drinking water guideline values and thus the potential health loss caused by these contaminants will be zero. A limitation of the approach is that DALY-outcomes often have a high amount of uncertainty, for instance due to the assumptions made on causality, dose-response effects and exposure assessment. This should be taken into account when performing a health impact assessment using DALYs for comparing different policy-measures or risk prioritization.

Contents

1 General introduction

Health loss due to exposure to (potentially) harmful chemical contaminants in drinking water can be predicted by a health impact assessment. A health impact assessment is defined by the WHO as a combination of procedures, methods and tools by which a policy, programme or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population. A health impact assessment can be used to determine which environmental factor or compound in drinking water has the greatest impact on public health. The exposure to various hazards that can be present in water may result in very different health outcomes. Some outcomes are mild (e.g. diarrhoea), while others can be severe (e.g. cholera or cancer); some are acute (e.g. diarrhoea), while others are delayed (infectious hepatitis or cancer).

The aim of this report is to give an introduction on the DALY-concept and discuss the usefulness of this method in human health impact assessment of exposure to drinking-water contaminants. In Chapter 2 we give a general introduction on the use of the DALY-concept in human health impact assessment. Chapter 3 describes several examples of the use DALYs to estimate the total burden of disease in the Netherlands and the health loss attributed to environmental, occupation and food factors. Chapter 4 gives examples of the application of DALYs in health impact assessment related to drinking water quality. In chapter 5, we present a general methodology to estimate human health loss caused by exposure to drinking water contaminants. To illustrate this methodology, a case study on seven genotoxic compounds is also presented in chapter 5. In the final chapter, a general discussion and future perspectives are given.

2 Introduction to the DALY-concept

In order to support public health priority setting a common metric is required that can be applied to all types of hazard and takes into account different health outcomes including risk of disease, severity and duration of effects. Disability Adjusted Life Years (DALYs) provide this metric. Expressing health impact in DALYs facilitates the comparison of a range of diverse health effects by taking into account severity and duration of the effects. The DALY concept was presented by Murray and Lopez in 1996 for the World Health Organization (WHO) [1] to compare death and disability from various disorders used to estimate the global burden of disease. DALYs represent the loss of health and are composed of two components: (1) the loss of quantity of life (years lost due to premature death), and (2) the loss of quality of life (years spent with a disease). The years spent with a disease are weighed according to the severity of the condition, using weighting factors. This renders the years spent with a disease comparable with those lost due to death. In this way, the lost life years and the disease year equivalents are enumerated as DALYs. For various diseases, DALYs are derived using statistical information about mortality rates, incidence or prevalence and seriousness of the disease [1].

For the calculation of DALYs, the following formula may be used: the sum of Years of Life Lost (YLL) and the Years Lived with Disability (YLD), with **DALY = YLL + YLD** (Figure 1)[2]. **YLL** is the number of years of life lost due to mortality and is calculated as the product of the number of deaths with the standard life expectancy at the age of death. **YLD** is the number of years lived with a disability, weighed with a factor between 0 and 1 for the severity of the disability or disease. YLD is thus calculated as the number of persons affected by a disease multiplied by the duration and the weighting factor for this disease (Figure 1). If necessary, disease processes are subdivided into several stages with different duration and severity [2].

DALY = YLL + YLD	
Years of Life Lost (YLL)	**Years Lived with a Disability (YLD)**
Number of deaths × Standard **life expectancy** at age of death in years	**Number** of people with disease × **Weighting factor** 0 (normal good health) to 1 (death) × **Duration** of the disease

Figure 1. Formulas used for the calculation of DALYs [2].

The weighting factors are derived by expert panels, and have a range between 0 (perfect health, no disability) to 1 (death, maximum health loss or severest disability) (Table 1). These weighting factors are

published by WHO and RIVM [3, 4]. For example, if a disease has a weighing factor of 0.5, this means that a year spent with this disease is considered equivalent to half a year lost due to premature death. For diseases in the Netherlands as published by RIVM, weighting factors were determined within the project 'Dutch Disability Weights'. The weighting factors were set by using expert judgment of medical experts, as knowledge and insight in the consequences of a large number of diseases are considered essential [5].

Table 1. Weighting factors for different diseases used in DALY calculations [4].

Disease	**Weighting factor for disease**
Dementia	0.71
Parkinson's disease	0.68
Lung cancer	0.54
Rheumatoid arthritis	0.53
Coronary heart disease	0.29
Diabetes mellitus	0.20
Injury caused by traffic accidents	0.17
Gastrointestinal infections	0.03
Influenza	0.01

The following example illustrates a DALY-calculation: A person develops lung cancer at the age of 45 and dies of it at the age of 59. The average life expectancy is set to 80 years. The number of years of life lost, YLL = 80-59 = 21 and with a weighting factor of 0.54 for lung cancer the number of years lived with disability, YLD = 0.54 x (59-45) = 7.6. So the total health loss for this person is calculated by YLL+YLD which sums up to 28.6 DALY. By using age-specific mortality and morbidity data together with the population size, this calculation can be carried out for populations instead of individuals. The result is an absolute number of DALYs for a population representing the health loss. The diagram in Figure 2 sketches the basic idea behind the DALY-concept [2].

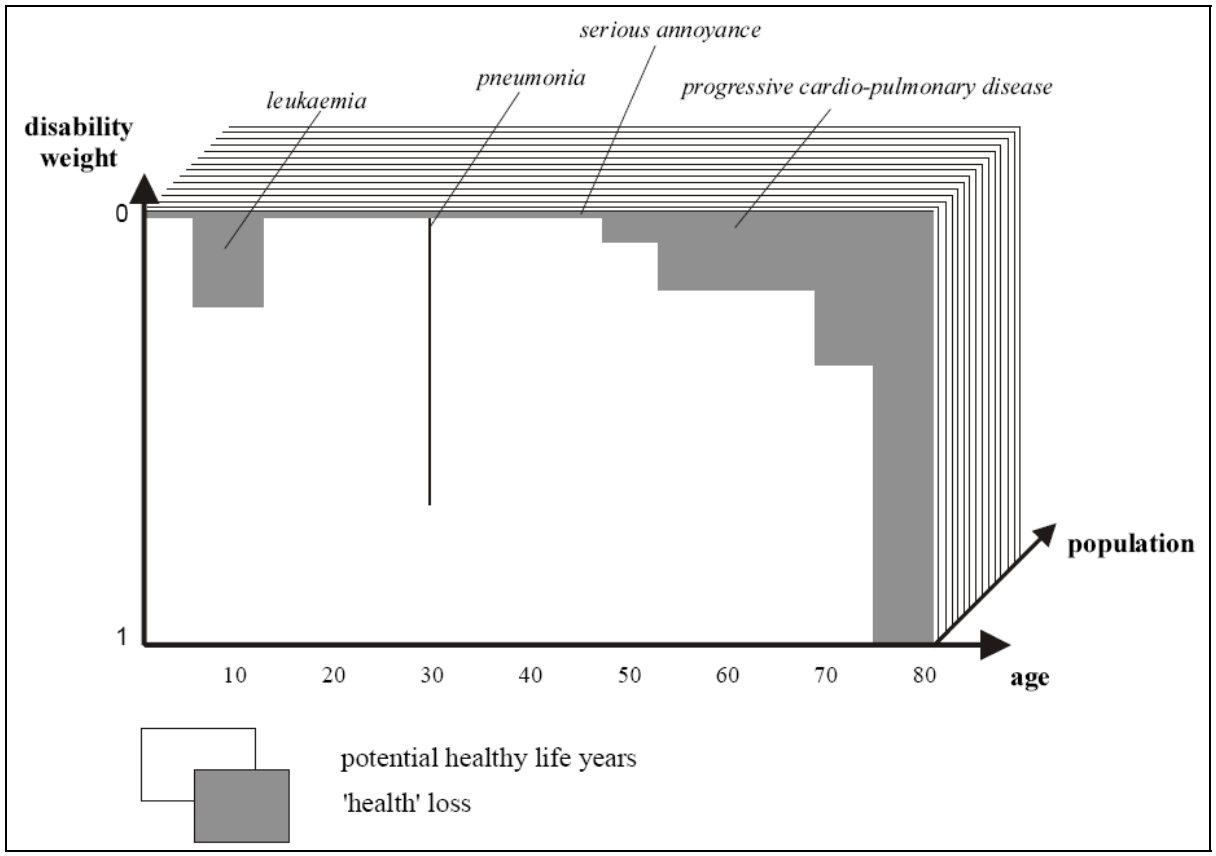

Figure 2. Diagram of the concept of DALYs (reproduced from [2]).

When performing a health impact assessment on drinking water contaminants, the health loss per case of disease caused by these contaminants is needed. Havelaar and colleagues derived DALYs for diseases caused by several drinking water contaminants and pathogens [2]. They obtained data on disease duration, course of the disease and mortality rates from epidemiological studies. The results are summarized in Table 2, expressed as disease burden per 1000 cases of disease. For example, an infection with rotavirus (in developed countries) causes [2, 6]:

- mild diarrhea (weighting factor of 0.1) lasting 7 days in 97.5% of cases
- severe diarrhea (weighting factor of 0.23) lasting 7 days in 2.5% of cases
- rare deaths of very young children in 0.015% of cases

The DALY per case of infection with rotavirus then equals to (0.1 x 7/365 x 0.975) + (0.23 x 7/365 x 0.025) + (1 x 80 x 0.00015) = 0.0019 + 0.0001 + 0.012 = 0.014. Then the health loss per 1000 cases is 2 (YLD) + 12 (YLL) = 14 DALYs.

Table 2. Summary of health loss in DALYs caused by different drinking-water contaminants [2]. The number of DALYs is expressed per 1000 cases of disease.

Contaminant	**Disease burden per 1000 cases of disease**		
	YLD	YLL	DALYs
C. parvum	1.3	0.1	1.5
Campylobacter spp	3.2	1.4	4.6
E. coli STEC O157	14	41	55
Rotavirus – high income countries	2	12	14
Rotavirus – low income countries	2	480	482
Hepatitis-A virus – high income countries	5	250	255
Hepatitis-A virus – low income countries	3	74	77
Bromate*	-	10,900	10,900
Arsenic*	-	54,000	54,000

* Disease burden is expressed as per 1000 cancer deaths

3 Use of DALYs in health impact assessment – public health context

This chapter describes several examples of the use of DALYs in human health impact assessment in the Netherlands. DALYs may be used as a metric to express the total burden of disease and providing information on public health in a country in a comparable way. For the Netherlands, the total burden of disease was estimated by RIVM in 2007 [7]. The results are presented in paragraph 3.2. Further, as an illustration, the results of several national studies on the burden of disease attributed to environmental factors, occupational factors, harmful substances in food and chemicals in non-food consumer products are given in paragraph 3.3 to 3.6.

3.1 Introduction

In general, to assess the health impact or the burden of disease by a certain factor (e.g. an environmental factor or a drinking water contaminant), the following aspects are taken into account [8]:

- selection of health endpoints
- assessment of population exposed and the height of exposure
- identification of exposure-response relationships
- estimation of extra number of cases with a specific health state
- selection of severity weights and duration of health effects
- computation of the total health burden of all risk factors

The approach of a health impact assessment differs from a traditional risk assessment at several aspects [9]. In general, a traditional risk assessment aims to derive a guideline value, i.e. an exposure limit below which no health effects are expected, whereas a health impact assessment gives insight in the health effects at a certain exposure level in an exposed population. In a traditional risk assessment, for exposure a worst case estimate is made on a personal basis. In a health impact assessment, a realistic estimate of the exposure is being made at a population level. Risk assessment focuses on parameters indicative for toxicity whereas health impact assessment focuses on manifest effects of disease. In risk assessment, a no-observed-adverse-effect-level (NOAEL) for the critical effect is defined. In health impact assessment exposure-response associations are derived based on development of a certain disease [9]. For a health impact assessment, human epidemiological data studying exposure-response relationships are preferred, despite that they are subject to potential biases. However, in reality most toxicological effects of compounds are only studied in animals, and human epidemiological data are often lacking or scarce. Therefore, extrapolations from animal to the human are necessary for a health impact assessment [9]. In some cases, this appears to be evident: the formation of tumors in animals translates into cancer

development in humans. However, for other effects, this translation provides problems. Effects on liver weights or liver enzyme activities might be used to establish a NOAEL in risk assessment, but linking these effects to a related human disease is not directly evident. Especially for reproduction toxicity, it is expected beforehand that it would be very difficult to translate toxicity effects into 'human disease' allowing expression in DALYs. For example, when infertility or fetal loss is found in an animal experiment, it is difficult if not impossible to extrapolate this to actual human health effects, and even more difficult to weight this into DALYs [9]. A traditional risk assessment is completely designed to access safety of a chemical i.e. they have been developed from the view of public health protection. Therefore, NOAELs in animal species are extrapolated to humans using so called assessment (or uncertainty) factors for inter- and intraspecies variation (in general 10x10=100) [9]. The basis for this philosophy is that in most cases we do not know whether humans are actually more or less sensitive for the effects of the chemical under investigation, but we assume humans are 10 times more sensitive than the average animal, or whether certain persons are more sensitive than others, again assuming a factor of 10. For obvious reasons, such extrapolations are always on the safe (conservative) side. In this way, the total system 'ensures' the protection of public health [9]. For a health impact assessment, we need to determine the true exposure and health effects as much as possible. The default extrapolation factor of 100 used in risk assessment is in this case probably not realistic. Because in reality these factors may be highly variable and even be smaller than one (in cases where humans are less sensitive than animals) [9]. In short, a risk assessment may be considered as 'protective', whereas a health impact is 'predictive' [9].

3.2 National burden of disease

The RIVM calculated the burden of disease expressed in DALYs for 56 diseases in the Netherlands in 2007 [7]. A selection of these calculations is presented in Table 3. To calculate the YLD in 2007, the duration of disease was set at 1 year. The YLL is calculated by the number of deaths multiplied by the standard life expectancy at the age of death (data not shown). The total burden of disease for the Dutch population is estimated at 4,500,000 DALYs per year, which equals to 273,000 DALYs/million person years (mpy)[1] [7]. No information is provided on the uncertainty of these estimates.

[1] Based on 16.5 million inhabitants in the Netherlands.

Table 3. Burden of disease of five selected diseases in DALYs in the Netherlands in 2007 [7].

Disease	**YLL**	**Number of disease × Weighting factor = YLD**	**DALYs**	**DALYs/mpy**
Coronary heart disease	128,000	648,300 × 0.29 = 187,000	315,000	19,000
Diabetes mellitus	34,000	668,500 × 0.20 = 132,000	166,000	10,000
Lung cancer	148,000	18,000 × 0.54 = 10,000	158,000	9,500
Dementia	44,000	79,000 × 0.71 = 56,000	100,000	6,000
Influenza	800	778,000 × 0.01 = 7,800	8,600	500

3.3 Environmental burden of disease

Within the Environmental Burden of Disease project (EBoDE project, 2009), the participating six European countries investigated to which extent the total burden of disease is caused by environmental factors [4]. Nine environmental factors were studied, which appeared to contribute to 3-7% of the yearly total burden of disease in the Netherlands. The highest contributors are particulate air pollution (6,000 – 10,000 DALYs/mpy) and noise (1,000 – 1,500 DALYs/mpy), followed by exposure to radon in buildings (600 – 800 DALYs/mpy), passive smoking (300 to 700 DALYs/mpy), lead exposure through drinking water (200-400 DALYs/mpy) and exposure to ozone by air pollution (40 – 200 DALYs/mpy). The three other estimates are 2-4 DALYs/mpy for exposure to benzene, 0-2 DALYs/mpy for formaldehyde and 0-400 DALYs for dioxin [4]. In total, the maximum amount of yearly health loss attributed to these nine environmental factors is estimated at 14,000 DALYs/mpy or 230,000 DALYs for the total population. The final report with the calculations is not available yet.

3.4 Occupational burden of disease

The RIVM also studied the burden of disease in the Netherlands caused by exposure to chemical agents in occupational settings [10]. They estimated this burden of disease at approximately 47,000 DALYs per year (or 2850 DALYs/mpy[2]), including about 1,900 deaths. Due to the lack of hard data the reliability of this estimate is limited. The margin of uncertainty is about a factor of 5 and is estimated to amount some 16,000 to 240,000 DALYs, including about 900 to 9,000 deaths. The two largest contributions are attributed to asthma and chronic obstructive pulmonary diseases (800 DALYs/mpy) and mesothelioma, lung cancer and asbestosis, all due to asbestos exposure (700 DALYs/mpy). Next to these, lung cancer

[2] Based on the total population in the Netherlands of 16.5 million inhabitants

(550 DALYs/mpy), contact dermatitis (350 DALYs), rhinitis and sinusitis (250 DALYs/mpy), and cardiovascular disorders (100 DALYs/mpy) are important contributors to the total burden of disease. Smaller contributions are produced by toxic inhalation injury (15 to 35 DALYs/mpy), chronic toxic encephalopathy (30 DALYs/mpy), and skin cancer (17 DALYs/mpy). In terms of contribution to the total burden of the investigated diseases in the Dutch population, occupational exposure to substances is responsible for practically 100% of the burden of disease due to mesothelioma, asbestos-related lung cancer and asbestosis, and also for 100% of the burden of disease due to chronic toxic encephalopathy and toxic inhalation injury. Contributions of 25 to 30% can be attributed to contact dermatitis and rhinitis plus sinusitis, and less than 10% for each of the other investigated diseases [10].

3.5 Burden of disease resulting from harmful substances in food

The RIVM calculated the health loss caused by (chemical) substances in our food [11]. The authors distinguished between acute effects, carcinogenic effects and allergenic effects. They estimated the health loss for the total Dutch population per year due to allergic proteins in food, such as fish, milk, nuts and wheat at 60 DALYs/mpy. Acute effects resulting from exposure to phycotoxins[3], phytotoxins[4] and growth promotors trough food ranges between 0.05 and 4 DALYs/mpy. Exposure to the carcinogenic compounds aflatoxin leads to a health loss of < 0.05 DALYs/mpy, nitrosamines to 6-30 DALYs/mpy, PAHs to 0.3-0.6 DALYs/mpy and acrylamide to 18-42 DALYs/mpy [11]. In total, the total health loss may be estimated at 130 DALYs/mpy for the selected case compounds. However, the authors state that, in most cases, it is not possible to give more than a very approximate estimate of the number of deaths and disability years for which these substances account. Weighing factors rely on analogy with conditions with a broadly comparable profile in terms of seriousness and duration. Accordingly, the figures should be seen as 'order of magnitude' estimates and are presented as such. Nevertheless, this case study showed that it is possible to compare the adverse health effects caused by exposure to various substances in our food [11].

3.6 Health impact assessment of policy measures for chemicals in non-food consumer products

Besides the use of DALYs for an estimation of the burden of disease caused by various factors, DALY calculations could also be used for health impact assessment of policy measures. The RIVM and TNO Quality of Life assessed the human health impact resulting from policy measures on the reduction of consumer exposure to nine chemicals in consumer products [9]. In this case study, they expressed the health gain in DALYs for the Dutch population. To this end, they estimated the exposure and the

[3] Marine biotoxins that accumulate in fish and shellfish from their diet (causing food poisoning when the fish are eaten by humans)
[4] any substance produced by plants that is similar in its properties to extracellular bacterial toxin

expected burden of disease before and after the implementation of the policy measure. Then the health gain was expressed as the difference between de burden of disease before and after the policy measure.

The so-called Nickel Directive regarding contact eczema due to allergy to nickel-containing products seemed to result in a successfully high level of health gain of 3000 DALYs. It is noted that the total burden of disease of contact eczema in the Netherlands in 2003 was about 30,000 DALYs. Furthermore, the cases of acute exposure to organic solvents by substances in do-it-yourself products (dichloromethane, toluene and volatile organic compounds) resulted in a health gain of about 100 DALYs for each compound. The number of DALYs derived for the carcinogenic substances from various consumer products range from zero (formaldehyde), few (nitrosamines, based on animal studies), to hundreds (acrylamide), thousands (azo dyes) or ten thousands (nitrosamines, based on human epidemiological studies). The authors state that this large range in health gain in DALYs are caused by differences in the level of exposure as well as differences in the potency of the carcinogenic substances, or by the size of the target population using a certain type of product.

4 Use of DALYs in health impact assessment – examples related to drinking water quality

In this chapter some examples from the literature of the application of DALYs in health impact assessment in the drinking water sector are outlined.

4.1 Health impact assessment of drinking water disinfection using ozone

Havelaar and colleagues describe an interesting example using DALYs as a measure to compare positive and negative health effects of drinking water disinfection [12]. They conducted a case study involving a hypothetical drinking water supply in the Netherlands which uses surface water for the production of drinking water. They compared the reduction of the risk of infection with *Cryptosporidium parvum* by ozonation of water to the concomitant increase in risk of renal cell cancer arising from the production of bromate. *C. parvum*, a protozoan parasite, produces highly infectious oocysts. Infection with *C. parvum* may result in self-limiting gastroenteritis in immuno-competent persons. In those who are immuno-compromised, the infection is not easily cleared and usually results in severe life-threating gastroenteritis. *C. parvum* oocysts may be inactivated by ozonation. However, ozone reacts with bromide ions present in raw water leading to the production of bromate. Bromate induces tumors in the rat kidney, thyroid and mesothelium and is a renal carcinogen in the mouse [13]. Bromate is considered the most important by-product of ozonation [14]. The authors concentrated on renal cell cancer as an outcome of chronic exposure to bromate. The authors did not take into account the presence of other disinfection by-products or other infectious organisms.

The authors estimated the median bromate concentration in this case study at 3.8 µg/L. Further, they calculated to daily ingested dose of *C. parvum* oocysts and bromate ions by multiplication of their concentration in drinking water with the daily consumption of uncooked drinking water (0.16 L) or total drinking water (0.81 L), respectively. The median body weight used in the estimations was 75 kg. Table 4 shows (part of) the results from this case study. In the scenario without ozonation, the median incidence of infection with *C. parvum* was estimated at 1,000 cases/mpy which leads to 710 cases of gastroenteritis. The median duration of the infection and the disability weight were estimated at 0.016 (6 days) and 0.054, respectively. The mortality due to *C. parvum* infection in the healthy population is low; 0.004 deaths per mpy. These numbers were mainly based on epidemiological data from the *C. parvum* outbreak in Milwaukee, Wisconsin in 1993. The authors estimated the standard life expectancy at the age of death at 8.2 years. Without ozone disinfection, the total health burden was 0.03 (YLL) + 0.61 (YLD) = 0.64 DALYs/mpy (Table 4) [12].

The introduction of an ozonation step in water treatment reduces the risk of infection with *C. parvum* approximately 5- to 6-fold leading to 130 cases of gastroenteritis per mpy and 0.001 deaths per mpy [12]. The authors estimated that the exposure to bromate through drinking water leads to 0.006 additional deaths of renal cell cancer per mpy. The excess lifetime risk of renal cell cancer was derived from dose-response data for induction of renal cell cancer by bromate in three rat studies [12]. The health loss of morbidity from renal cell cancer is negligible; premature death costs 10 years of the standard life expectancy. After ozonation, the total health burden was 0.07 (YLL) + 0.11 (YLD) = 0.18 DALYs/mpy. The net health benefit due to ozonation in this case study is estimated at 0.64 – 0.18 = 0.46 DALYs/mpy. Besides the net benefit in the healthy population, the authors also considered a more susceptible subgroup of persons which have an immunodeficiency i.e. AIDS patients. In these immuno-compromised persons, an infection with *C. parvum* may not easily be cleared and usually results in a life-threatening gastroenteritis. When this subgroup was taken into account, they calculated a net health benefit of 0.7 DALYs/mpy.

This case study showed the application of the DALY-concept in balancing the risks and benefits of drinking water disinfection. The results showed that the health benefits of preventing gastroenteritis and premature death due to ozonation outweigh the health loss by premature death due to renal cell cancer caused by bromate. However, the absolute health gain of 0.5 to 0.7 DALYs/mpy in this case study is a relatively small fraction of the total burden of disease. Further, the authors state that the application of DALYs may be hampered by the substantial degree of uncertainty, as is typical for risk assessment.

Table 4. Health loss in DALYs without and with ozonation of drinking water (per million person-year) (adapted from [12]).

	No ozone	With ozone
Years of Life Lost (number x life expectancy)	0.004 x 8.2 = 0.03	0.001 x 8.2 + 0.006 x 10 = 0.07
Years lived with disability (number x duration x weighting factor)	710 x 0.016 x 0.054 = 0.61	130 x 0.016 x 0.054 = 0.11
Total DALYs/mpy	0.64	0.18

See text for explanation of the figures.

4.2 Examples of health impact assessment of other drinking water contaminants or pathogens

Three other examples of DALY calculations in health impact assessments for drinking water contaminants were found in the literature.

- De Hollander et al. (1999) calculated the Dutch burden of disease caused by the presence of lead in water from drinking water pipes based on the situation in 1990 [15]. They estimated the yearly health loss caused by neurocognitive development deficits (lower IQ) due to lead exposure through drinking water at 8,000 DALYs for the Dutch population (5th-95th percentile 1,000 to 19,000), which equals 485 DALYs/mpy (ranging from 60 to 1150 DALYs/mpy). No details on the calculation were provided in this publication.
- Fewtrell et al. estimated the global burden of disease due to skin lesions caused by arsenic in drinking water by combining country-based exposure data with selected exposure–response relationships derived from the literature [16]. Populations were considered to be exposed to elevated arsenic levels if their drinking water contained arsenic concentrations of 50 mg/L or greater. Elevated arsenic concentrations in drinking water result in a significant burden of disease at the global level (ranging from 1,500 to 6,700 DALYs/mpy in the exposed population). At the regional level, the persons living in Bangladesh, India and Nepal were particularly badly affected (roughly 5,000 to 25,000 DALYs/mpy). More severe cancer-related health outcomes were not taken into account in this study. The estimate derived in this paper relied on limited exposure–response data and relatively crude exposure data and is, thus, subject to a large degree of uncertainty. It does, however, represent an important initial attempt to quantify this public health problem.
- Ciketic et al. recently examined the cost-effectiveness of fluoridation of drinking water supplies for Brisbane and South East Queensland, Australia [17]. The benefits conveyed were expressed in reduced costs of dental treatment and years of life with dental caries as a disability. They showed that if fluoridation (1 ppm) was implemented there would be a total saving of 10,000 DALYs and 666 million Australian dollars. Their conclusion was that fluoridation remains a very cost-effective measure for reducing dental decay as more DALYs were saved along with significant cost saving.

Several examples of DALY calculations in health impact assessments for pathogens present in water were found in the literature. Japanese investigators performed a quantitative risk assessment of noroviruses in drinking water using DALYs [18]. Further, Fewtrell and Kay describe several case-studies on health impact assessment for different water management policy measures in the UK [19]. These examples comprise DALY-calculations for risk of injury and drowning and microbiological risks in water management developments such as rainwater harvesting, greywater reuse, and evaluations of health impact of flooding for the UK population.

4.3 Use of DALYs in establishing guideline values for drinking water

The DALY-concept may also be used to establish health based guideline values for drinking water, which is outlined in the WHO Guidelines for drinking-water quality [6, 20]. The WHO reference level of risk is set at 1 DALY/mpy, which equals to 10^{-6} DALYs per person per year. For carcinogenic substances, this is approximately equivalent to a lifetime excess cancer risk of 10^{-5}, i.e. 1 excess case of cancer per 100,000 of the population ingesting drinking water containing the genotoxic substance at the guideline value over a life span. For countries that use a stricter definition of the level of acceptable risk of carcinogens (such as 10^{-6} in the Netherlands), the tolerable loss will be proportionately lower (such as 0.1 DALYs/mpy) [20]. This approach may also be used for pathogens in drinking water. To illustrate this methodology, the WHO calculated the maximum level of organisms per liter drinking-water for *Cryptosporidium parvum*, *Campylobacter* and rotavirus based on this reference level of risk of 1 DALY/mpy (Table 5) [20]. They estimated the probability of infection as the product of the exposure by drinking-water (1 L raw drinking water per day) and the probability that exposure to one organism would result in infection. They assumed that different exposure events are independent, in that no protective immunity is built up. This simplification is justified for low risks only. Not all infected individuals will develop clinical illness; asymptomatic infection is common for most pathogens. The percentage of infected persons that will develop clinical illness depends on the pathogen, but also on other factors, such as the immune status of the host. Risk of illness per year was obtained by multiplying the probability of infection by the probability of illness given infection. The DALYs per case used in the calculation are presented in Table 2 [2] (see above). At the WHO reference level of risk of 10^{-6} DALYs per person per year and taking into account the disease burden per case, the risk of infection, the risk of disease upon infection and the susceptible population, the maximum level of organisms per liter for *C. parvum*, *Campylobacter* and rotavirus were 6.3×10^{-4}/L, 1.3×10^{-4}/L and 3.2×10^{-5}/L, respectively (Table 5) [20]. This equals to one organism per 1600 L, 8000 L and 31,000 L, respectively.

Table 5. Example of calculations of the maximum level of organisms per liter raw drinking-water based on a reference 10^{-6} risk level. Adapted from [20].

			C. parvum	*Campylobacter*	Rotavirus
A	Drinking-water quality	Organisms per litre	6.3×10^{-4}	1.3×10^{-4}	3.2×10^{-5}
B	Consumption of unheated water	Litres per day	1	1	1
C	Exposure	Organisms per day (= A x B)	6.3×10^{-4}	1.3×10^{-4}	3.2×10^{-5}
D	Dose response	Probability of infection per organism	4.0×10^{-3}	1.8×10^{-2}	2.7×10^{-1}
E	Risk of infection	Risk per year (= C x D x 365)	9.2×10^{-4}	8.3×10^{-4}	3.1×10^{-3}
F	Risk of illness given infection		0.7	0.3	0.5
G	Risk of illness	Risk per year (= E x F)	6.4×10^{-4}	2.5×10^{-4}	1.6×10^{-3}
H	Disease burden	DALYs per case	1.5×10^{-3}	4.6×10^{-3}	1.4×10^{-2}
I	Susceptible fraction	Percentage of the population	100%	100%	6%
J	Disease burden	DALYs per year (= G x H x I)	1×10^{-6}	1×10^{-6}	1×10^{-6}

5 Case study on health impact assessment for drinking water contaminants

5.1 Methodology

In this chapter, we present a case study in which we performed a health impact assessment for several drinking water contaminants. We calculated the lifetime cancer risk and the annual health loss in DALYs for exposure to (potential) genotoxic carcinogens in drinking water, which are regulated by the Dutch statutory guidelines ('Drinkwaterbesluit 2011'). In this hypothetical case study, we used a scenario of a theoretical lifelong exposure to drinking water containing on average the maximum allowable concentration of these contaminants for the total Dutch population. Based on the DALY-concept, we propose to estimate the health loss attributable to drinking-water contaminants by using the following methodology (based on [2]):

1) Estimate the number of people affected (N). For genotoxic carcinogens, the lifetime additional cancer risk for the exposed population at a given contaminant concentration is derived using the general approach of quantitative risk extrapolation from the excess lifetime 10^{-6} cancer risk [20]. Then, the number of affected people may be calculated by multiplication of the additional lifetime cancer risk with the exposed population (in this case study 16.5 million people). In this calculation we used an average body weight of 70 kg and an average daily water consumption of 2 L.
2) Estimate the average duration of the adverse health response, including loss of life expectancy as a consequence of premature mortality (D).
3) Attribute weights for severity to the unfavorable health conditions (S).
4) Calculate the health loss in DALYs at a theoretical lifetime exposure, using the equation: DALYs = N × D × S. The health loss in DALYs per year is then calculated by dividing the total health loss over a life span of 75 years (standard life expectancy), assuming a steady state population.

In most cases, the risk estimates of lifetime exposure to the carcinogens were obtained from the background documents of the WHO Guidelines for drinking-water quality. In, addition a literature search was performed for additional epidemiological or animal study data.

Table 6 presents the selected carcinogenic compounds for this case study and their corresponding guideline values. Other categories of compounds, including non-genotoxic carcinogens, were not taken into account, because no human health effects are expected at guideline values which are set below the threshold value for toxic effects [20]. In addition, all metals stated in the Dutch statutory guideline values ('Drinkwaterbesluit', Table II chemical parameters) were excluded in this case study due to time limitations: antimony, arsenic, boron, cadmium, chromium, nickel and selenium. Despite the

fact that most of these metals or their sub-forms may be (possibly) carcinogenic to humans; depending on the route of exposure [20]. Further, the group parameters PAHs, PCBs and pesticides were also excluded due to time constraints. The compound epichlorohydrin is considered a genotoxic carcinogen. However, this compound was not included in this case study because the use of a linearized multistage model for estimating excess cancer risk was considered inappropriate as tumors are seen only at the site of administration, where epichlorohydrin is highly irritating [21]. Trichloroethene is also considered a genotoxic carcinogen and classified by IARC in Group 2A (probably carcinogenic to humans) [22]. However, trichloroethene was not included in this case study because developmental toxicity is considered as the critical effect [22].

Table 6. Drinking-water guideline values of potential carcinogenic compounds.

Compound	**Guideline value Drinkwaterbesluit 2011 (µg/L)**
Acrylamide	0.1
Benzene	1.0
Benzo(a)pyrene (BaP)	0.01
Bromate	5.0
1,2-dichloroethane	3.0
Nitrosodimethylamine (NDMA)	0.012
Vinyl chloride	0.1

5.2 Acrylamide

In this paragraph, the theoretical annual health loss for a lifelong average exposure to 0.1 µg/L acrylamide through drinking water is derived (0.003 µg acrylamide/kg bw/day for adults). In a long-term carcinogenicity study in rats exposed via drinking-water, acrylamide induced tumors at various sites. The IARC has placed acrylamide in Group 2A (probably carcinogenic to humans) [23]. There are epidemiological indications that dietary acrylamide might cause cancer in humans, and the indications are strongest for postmenopausal endometrial and ovarian cancers [24].

On the basis of combined mammary, thyroid and uterine tumors observed in female rats in a drinking-water study and using the linearized multistage model, WHO estimated the upper-bound excess lifetime cancer risk of 10^{-6} at 0.05 µg/L [23]. A source of drinking-water contamination by acrylamide may be the use of polyacrylamide flocculants that contain residual acrylamide monomer [23]. Human studies showed that the risks observed in human studies for endometrial, ovarian, and renal cell cancers are at least 10-fold to 100-fold higher than what would have been expected from the animal studies. However, no estimates of the excess cancer risk were provided in this publication [24]. The current intake level of acrylamide via food is 0.3 to 0.8 µg/kg body weight/day [24].

A lifelong exposure to 0.003 µg/kg bw/day (0.1 µg/L) acrylamide results in an additional carcinogenic risk of 2 per 1 million exposed people based on the excess 10^{-6} lifetime cancer risk provided by the WHO [23]. Then the estimated number of affected persons in the Netherlands is 2 × 16.5 = 33 (N). Human epidemiological studies showed associations between acrylamide exposure and development of various forms of cancer, such as endometrial, ovarian and renal cell cancers [24]. Therefore, a standardized DALY of 9 is used for each person developing tumors (D × S). This standardized DALY of 9 was calculated by RIVM based on the seven most frequently occurring types of cancer in the Netherlands [7]. The health loss in the Netherlands due to a theoretical lifelong exposure to 0.1 µg/L acrylamide by drinking water equals 33 × 9 = 297 DALYs. Per year (based on a life expectancy of 75 years), the DALY by acrylamide in drinking water is **4** for the whole Dutch population (or 0.2 DALYs/mpy).

5.3 Benzene

In this paragraph DALYs are derived for a theoretical lifelong average exposure to drinking water containing 1 µg/L benzene. For adults, this intake equals to 0.03 µg/kg bw/day. Benzene is carcinogenic in mice and rats after both inhalation and oral exposure, producing malignant tumors at many sites. It is considered to be a human carcinogen [25]. As epidemiological data on the carcinogenic risk to humans following the ingestion of benzene are not available, risk estimates were carried out on the basis of a 2-year gavage study in rats and mice [25]. The estimated concentration range in drinking-water corresponding to excess lifetime cancer risks of 10^{-6}, based on leukemia and lymphomas in female mice and oral cavity squamous cell carcinomas in male rats, is 1 - 8 µg/L. Then, the WHO guideline value for benzene in drinking-water corresponding to excess lifetime cancer risks of 10^{-6} is established at 1 µg/L [25].

A lifelong exposure to 0.03 µg/kg bw/day (1 µg/L) benzene equals to an additional carcinogenic risk of 1 per 1 million exposed people. Then the estimated number of affected persons the Netherlands is 1 × 16.5 = 16.5 (N). Although the mode of action of benzene-induced tumor formation is not clear, a linear dose-response relationship is considered. As the ratio for the development of tumors is unknown and the impact on illness is difficult to describe (e.g. age at cancer diagnosis, length of illness period, medical treatment effects and/or recovery of death ratio), a standardized DALY of 9 is used for each person developing tumors (D × S). This standardized DALY of 9 was calculated by RIVM based on the seven most frequently occurring types of cancer in the Netherlands [7]. Based on this data and assumptions the DALYs can be calculated by: 16.5 × 9 = 149 DALYs. The health loss in the Netherlands due to a theoretical lifelong exposure to 1 µg/L benzene by drinking water equals 149 DALYs. Per year (based on a life expectancy of 75 years), the DALY by benzene in drinking water is **2** for the whole Dutch population (or 0.1 DALYs/mpy).

5.4 Benzo(a)pyrene

In this paragraph DALYs are derived for a theoretical lifelong average exposure to drinking water containing 0.01 µg/L benzo(a)pyrene (BaP). For adults, this intake equals to 0.0003 µg/kg bw/day. If BaP is present in drinking-water at significant concentrations, this may indicate the presence of coal tar particles, which may arise from seriously deteriorating coal tar linings (see also BTO report 2010.044). BaP shows genotoxic properties in a variety of *in vitro* tests with metabolic activation and in *in vivo* studies [26]. IARC has placed BaP in Group 1 (carcinogenic to humans) [27]. Oral administration of BaP induces tumors of the forestomach in mice and mammary gland tumors in rats. BaP has produced skin tumors after dermal application and lung and respiratory tumors when administered intratracheally in rodents [26]. Evidence that mixtures of polynuclear aromatic hydrocarbons (including BaP) are carcinogenic to humans comes primarily from occupational studies of workers following inhalation and dermal exposure [26]. No data are available for humans for the oral route of exposure. Therefore, it is not possible to assess directly the risk of BaP to humans for the oral route [26].

Based on rodent studies, the WHO calculated an excess lifetime cancer risk of 10^{-6} as 0.07 µg/L [26]. A lifelong average exposure to drinking water containing 0.01 µg/L BaP leads to 0.01/0.07 × 16.5 = 2.4 affected persons (N). As no human oral exposure data are available, a standardized DALY of 9 is used for each person developing tumors (D × S) [7]. Based on WHO data, the health loss in the Netherlands due to a theoretical lifelong exposure to 0.01 µg/L BaP by drinking water is estimated at 2.4 × 9 = 21 DALYs. Per year (based on a life expectancy of 75 years), the DALYs by BaP in drinking water is **0.3** for the whole Dutch population (or 0.02 DALYs/mpy).

5.5 Bromate

In this paragraph DALYs are derived for a theoretical lifelong average exposure to drinking water containing 5 µg/L bromate. For adults, this intake equals to 0.14 µg/kg bw/day. Bromate is mutagenic both *in vitro* and *in vivo*. IARC has classified bromate in Group 2B (possibly carcinogenic to humans), concluding that there is inadequate evidence of carcinogenicity in humans but sufficient evidence of carcinogenicity in experimental animals [13]. Bromate has been shown to induce tumors in the rat kidney, thyroid and mesothelium and is a renal carcinogen in the mouse as well [13]. In this case study, we concentrate on renal cell cancer as an outcome of chronic exposure to bromate. No human epidemiological studies are available in the literature.

Based on animal studies, the WHO calculated an excess lifetime cancer risk of 10^{-6} at 0.007 µg/kg/day [13]. Then, the number of affected persons is 0.14 /0.007 × 16.5 = 352 for a lifelong average exposure to drinking water containing 5 µg/L bromate. The disease burden of bromate related renal cell cancer is estimated at 10.9 DALYs per renal cell cancer case (D × S), taking into account the case-fatality ratio per age class, the severity weight and duration [2]. Based on the WHO data, the health loss in the Netherlands due to a theoretical lifelong exposure to 5 µg/L bromate by drinking water equals 352 × 10.9

= 3835 DALYs. Per year (based on a life expectancy of 75 years), the DALYs by bromate in drinking water is **51** for the whole Dutch population (or 3 DALYs/mpy). The study by Havelaar et al (see paragraph 4.1) estimated an excess lifetime cancer risk of 10^{-6} at 0.16 µg bromate/kg bw/day by using three data sets fitted by two-stage models [12]. When using this 20-fold lower risk, the resulting a health loss is (0.14/0.16 × 16.5) × 10.9 = 147 DALYs for a lifelong exposure to 5 µg/L bromate. Per year, the health loss by bromate in drinking water is **2** DALYs for the whole Dutch population (or 0.1 DALYs/mpy).

5.6 1,2-dichloroethane

In this paragraph, the theoretical annual health loss for a lifelong average exposure to 3 µg/L 1,2-dichloroethame through drinking water is derived (0.086 µg /kg bw/day for adults). 1,2-Dichloroethane is used mainly as an intermediate in the production of vinyl chloride and other chemicals and to a lesser extent as a solvent. It may enter surface waters via effluents from industries that manufacture or use the substance. It may also enter groundwater, where it may persist for long periods, following disposal in waste sites [21]. IARC has classified 1,2-dichloroethane in Group 2B (possible human carcinogen). It has been shown to induce a number of tumor types in laboratory animals, including the relatively rare haemangiosarcoma, and the balance of evidence indicates that it is potentially genotoxic [21]. Targets of 1,2-dichloroethane toxicity in orally exposed animals include the immune system, central nervous system, liver and kidney [21]. Human epidemiological studies showed an association with lymphatic, haematopoietic, pancreatic and stomach cancers. All studies included workers with potential exposure to multiple agents and were not able to examine the excess risk associated with 1,2-dichloroethane [21].

On the basis of haemangiosarcomas observed in male rats in a oral gavage study and applying the linearized multistage model, a concentration in drinking-water of 3 µg/L, corresponds to a lifetime excess cancer risks of 10^{-6} [21]. Then, a lifelong average exposure to drinking water containing 3 µg/L 1,2-dichloroethane leads to 1 × 16.5 = 16.5 affected persons (N). As no human oral exposure data are available, a standardized DALY of 9 is used for each person developing tumors (D × S) [7]. Based on WHO data, the health loss in the Netherlands due to a theoretical lifelong exposure to 3 µg/L 1,2-dichloroethane by drinking water is estimated at 16.5 × 9 = 149 DALYs. Per year (based on a life expectancy of 75 years), the DALYs by 1,2-dichloroethane in drinking water is **2** for the whole Dutch population (or 0.1 DALYs/mpy).

5.7 Nitrosodimethylamine

In this paragraph DALYs are derived for a theoretical lifelong average exposure to drinking water containing 0.012 µg/L nitrosodimethylamine (NDMA). For adults, this intake equals to 0.00034 µg/kg bw/day. NDMA can occur in drinking-water through the degradation of dimethylhydrazine (a component of rocket fuel) as well as from several other industrial processes. It is also a contaminant of

certain pesticides [28]. NDMA has recently been identified as a disinfection by-product of chloramination (by the reaction of monochloramine with dimethylamine, a ubiquitous component of waters impacted by wastewater discharges) and, to some extent, chlorination. NDMA can also be formed as a by-product of anion-exchange treatment of water [28]. Further, NDMA may also be formed as a byproduct when using ozone for drinking water treatment in the presence of breakdown products from the fungicide tolylfluanide (see BTO reports 2009.058 en 2009.066). NDMA has been classified by IARC as probably carcinogenic to humans (Group 2A). There is conclusive evidence that NDMA is a potent carcinogen in experimental animals by several routes of exposure, including through ingestion of drinking-water [28]. Although there have been several case–control studies and one cohort study of NDMA in humans, none of them can be used to derive a quantitative risk of cancer [28]. The results are supportive of the assumption that NDMA consumption is positively associated with either gastric or colorectal cancer. However, none of the studies focused on drinking-water as the route of exposure; instead, they used estimations of total dietary intake of NDMA [28].

Based on animal studies, the RIVM calculated an excess lifetime cancer risk of 10^{-6} at a drinking-water concentration of 0.012 µg NDMA/L [29]. Then, a lifelong average exposure to drinking water containing 0.012 µg NDMA/L leads to $1 \times 16.5 = 16.5$ affected persons (N). As both stomach and various forms of tumors are described related to NDMA, a standardized DALY of 9 is used for each person developing tumors (D × S). This standardized DALY of 9 was calculated by RIVM based on the seven most frequently occurring types of cancer in the Netherlands [5]. The health loss in the Netherlands due to a theoretical lifelong exposure to 0.012 µg NDMA/L through drinking water equals to $16.5 \times 9 = 149$ DALYs. Per year (based on a life expectancy of 75 years), the DALY by NDMA in drinking water is **2** for the whole Dutch population (or 0.1 DALYs/mpy).

5.8 Vinyl chloride

In this paragraph DALYs are derived for a theoretical lifelong average exposure to drinking water containing 0.1 µg/L vinyl chloride. For adults, this intake equals to 0.003 µg/kg bw/day. Migration of vinyl chloride monomer from unplasticized PVC may be a possible source of vinyl chloride in drinking-water [30]. In addition, vinyl chloride has been reported in groundwater as a degradation product of the chlorinated solvents trichloroethene and tetrachloroethene [30]. Animal data show vinyl chloride to be a multisite carcinogen. When administered orally or by inhalation to mice, rats and hamsters, it produced tumors in the mammary gland, lungs, skin and liver [30]. There is sufficient evidence of the carcinogenicity of vinyl chloride in humans from industrial exposure to high concentrations of vinyl chloride via the inhalation route [30]. Among workers employed in the vinyl chloride industry have shown there was a marked exposure–response relation for liver cancers, angiosarcomas and hepatocellular carcinomas [30]. IARC has classified vinyl chloride in Group 1 (Carcinogenic to humans).

Based on animal studies, the WHO calculated an excess lifetime cancer risk of 10^{-6} at 0.0009 µg vinyl chloride/kg bw/day [30] for exposure from birth. Then, the number of affected persons (N) is 0.003 /0.0009 × 16.5 = 55 for a lifelong average exposure to drinking water containing 0.1 µg/L vinyl chloride. As various forms of tumors are described related to vinyl chloride, a standardized DALY of 9 is used for each person developing tumors (D × S). This standardized DALY of 9 was calculated by RIVM based on the seven most frequently occurring types of cancer in the Netherlands [5]. The health loss in the Netherlands due to a theoretical lifelong exposure to 0.1 µg/L vinyl chloride through drinking water equals to 55 × 9 = 495 DALYs. Per year (based on a life expectancy of 75 years), the DALY by vinyl chloride in drinking water is **7** for the whole Dutch population (or 0.4 DALYs/mpy).

5.9 Summary

Table 7 gives an overview of the calculated health loss in DALYs for the drinking water contaminants selected for this case study.

Table 7. Health loss resulting from a theoretical lifetime exposure to case compounds at drinking-water guideline values expressed in DALYs for the total Dutch population.

Case compound	**Health loss in DALYs for lifetime exposure**	**Health loss in DALYs per year**	**Health loss in DALYs/mpy***
Acrylamide	297	4	0.2
Benzene	149	2	0.1
Benzo(a)pyrene	21	0.3	0.02
Bromate	3835 (based on [13]) 147 (based on [12])	51 2	3 0.1
1,2-dichloroethane	149	2	0.1
NDMA	149	2	0.1
Vinyl chloride	495	7	0.4

*mpy = million person-years

6 General discussion and conclusion

6.1 Discussion

This report gives an overview on the usefulness of the DALY concept in human health impact assessment, with special focus on drinking water contaminants. As shown in chapter 3, the total burden of disease for the total Dutch population is estimated at 273,000 DALYs/mpy [7]. Of this total burden of disease, roughly 5% may be attributed to nine environmental factors (14,000 DALYs/mpy) [4] and roughly 1% to occupational exposure to chemical agents (2,850 DALYs/mpy) [10]. The health loss caused by the presence of a selection of toxic compounds in food was estimated at 130 DALYs/mpy (0.04%), which should be considered as a rough indication [11]. Further, this report gives several examples from the literature on the application of the DALY concept in comparing different policy measures or management options, e.g. expressing the health gain resulting from several policy measures on the reduction of consumer exposure to chemicals in consumer products and health impact assessment of drinking water disinfection using ozone. The case study by Havelaar et al. showed the application of the DALY-concept in balancing the risks and benefits of drinking water disinfection. The results showed that the health benefits of preventing gastroenteritis and premature death due to ozonation outweigh the health loss by premature death due to renal cell cancer caused by bromate formation [12]. The absolute health gain amounted to 0.5 - 0.7 DALYs/mpy, which is a relatively small fraction of the total burden of disease. This case study nicely showed the applicability in comparing public health risks and benefits of different management options. However, the authors also state that a major disadvantage of the method is the uncertainty in the calculations.

This report gives an overview of the health loss attributed to several different factors in the Netherlands. The results are summarized in the following table:

	Health loss in DALYs/mpy in NL
Total burden of disease	273,000
Environmental burden of disease (nine factors)	14,000
Occupational burden of disease	2,850
Harmful substances in food (selection of case compounds)	130
Health gain by drinking water ozonation	0.5
Theoretical exposure to genotoxic carcinogens through drinking water at guideline value	0.01 to 3 per compound

In this report, we present a general methodology to estimate human health loss caused by exposure to drinking water contaminants. As an illustration of this concept, we performed a case study on a hypothetical worst-case exposure to seven genotoxic drinking water contaminants. The total health loss resulting from a theoretical lifelong exposure to the case compounds at guideline value levels through drinking water ranges from 0.02 to 3 DALYs/mpy. This number is very low compared to the total health loss resulting from environmental factors of 14,000 DALYs/mpy. This case study only gives an indication on the theoretical health loss which may be caused by genotoxic drinking water contaminants, if the concentrations were around guideline values. In real life, however, concentrations of the selected genotoxic contaminants in drinking water are lower than the guideline value, which implicates that we make an overestimation of the potential health impact. For illustrative purposes, we also aimed to calculate the health loss in DALYs/mpy at average drinking water concentrations using water quality data from the REWAB-database (finished drinking water, years 2008-2010). For bromate, the highest average reported concentration in drinking water was 3.9 µg/L, which is below the guideline value of 5 µg/L. A lifetime exposure to drinking water containing 3.9 µg/L bromate may result in a health loss of 2.3 DALYs/mpy (= 3.9/5 x 3; based on reference [13]) or 0.08 DALY/mpy (= 3.9/5 x 0.1; based on [12]). For the compounds acrylamide and NDMA currently no data are available in the REWAB database. The compounds benzene, benzo(a)pyrene, 1,2-dichloroethane and vinylchloride were all reported at levels below the limit of detection in finished drinking water. At some laboratories the limits of detection for these compounds were equal to the guideline value which makes an estimation of the 'real' concentration in drinking water not possible. Therefore it is not possible to give a better or more precise estimate of the potential health loss in DALYs than already showed in our case study.

Non-genotoxic carcinogenic compounds and other toxic compounds with a so-called 'threshold effect' were not taken into account in this case study, because no effects on human health are expected at concentrations around or below guideline values, which are set below the threshold value for toxic effects [20]. For exposure to these compounds at guideline value level, no health loss is expected and therefore the DALY will be 0.

As mentioned earlier, the WHO reference level of risk for carcinogens is set at 10^{-6} DALYs per person per year or 1 DALY/mpy based on a lifetime excess cancer risk of 10^{-5} (chapter 4) [20]. In the Netherlands, we use a stricter definition of the acceptable lifetime excess cancer risk of 10^{-6}, which is equivalent to 10^{-7} DALYs per person per year or to 0.1 DALY/mpy. This implicates that for exposure to potential carcinogens through the environment, food or water, about 2 DALYs per year per compound are generally considered as 'acceptable', i.e. the expected health loss in DALYs at environmental concentrations around the guideline values. As expected, most of our DALY calculations gave results close to this value, as similar studies were used to derive the lifetime excess cancer risk.

Our case study presents a straightforward way to calculate DALYs. If good epidemiological data is available, then better estimates could be made for the YLD due to disease (age at onset of disease) and YLL due to mortality, specific for the type of tumors caused by exposure to the case compounds. In the current case study, for all genotoxic compounds except bromate, no information was available on the type of tumors which may develop upon exposure. This resulted in the use of a standardized DALY of nine for each person developing tumors (D x S) as derived by RIVM [7]. However, more specific estimates could be made if good data were available as different types of cancers have different severities, manifested mainly by different mortality rates. In the present case study, we did not make an effort to give an estimation of the uncertainty of the calculated number of DALYs. When comparing or prioritizing different policy measures, more effort should be put in uncertainty assessment.

In a paper of Crettaz and co-workers, an approach is presented to provide generic health loss estimates in '*numbers of years lost/mg intake*' for genotoxic contaminants [31]. This methodology is based on the benchmark dose BMD10 which is increasingly applied in risk assessment on genotoxic contaminants, e.g. by US EPA [32, 33]. This dose is defined as the 95% lower confidence limit on the dose producing a 10% response over background. The authors introduced in a similar way an effect dose ED10 as maximum likelihood estimate of the dose corresponding to a 10% response over background [31]. This ED10 dose is subsequently used as point of departure for linear extrapolation towards lower doses resulting in slope factors representing the likelihood of the genotoxic effect. These slope factors were combined with the DALYs per person to provide a severity-based toxicological measure of potential consequences associated with time-averaged exposure over a life span to a given quantity of a chemical

[31]. For genotoxic contaminants with good quality animal data, this method may be explored in future studies.

All different studies described in this report showed that the use of the DALY-concept in health impact assessment can provide an insight in attribution of different factors to the total burden of disease or health gain or health loss by policy measures or interventions. However, many authors mention that adequate prediction of the health effects in the population is quite difficult [8-12, 34]. DALY outcomes often have a large margin of uncertainty due to uncertainty in the data used for the calculations. In the health loss calculations, the variables such as exposure assessment data and exposure-response relationships, are added, contributing to greater total uncertainty of the output [8]. When using DALYs for health impact assessment of exposure to certain contaminants, an essential assumption is that of causality, as it is for any type of impact indicators [8]. However, certainty on a possible causal relationship is often lacking, due to scarce human epidemiological data of good quality. Furthermore, people argue that the method is -at least partly- subjective, since the severity values of health conditions (which can range from 0 (perfect health) to 1 (death)) are assigned by 'expert panels'[8]. Some observed adverse health effects in laboratory animals, which are highly suitable for risk assessment and setting guideline values, cannot be directly translated into a disease in humans. In addition, the time of onset of the disease is hard to define. Therefore, it is advisable to use health impact assessments based on the DALY concept only for priority setting, i.e. making the distinction between policy measures that contribute very little or very much to health impacts or to prioritize the contribution of exposure to chemical contaminants of pathogens [9]. However, some people address the very essence of the DALY-method by discussing whether it is ethically sound to quantify health and prioritize health problems [8]. Based upon the publication of Viscusi and Aldy, DALYs were monetarized by 70,000 euro per DALY [35]. This could be used when comparing expenses involved in policy measures or investments with the resulting health gain in monetary terms. The amount of money per DALY is comparable to the 80,000 euro per healthy life year recommended in the Netherlands as a limit for medical interventions [36].

6.2 Conclusion and future perspectives on health impact assessment of drinking water contaminants

As shown in this report, many studies emphasize the valuable use of DALYs to express the burden of disease or health loss by a specific factor. Recently, even a software tool has been developed to prioritize risks based on the DALY-concept, which could be used to evaluate pathogens, toxins and chemical contaminants in food [37]. However, as discussed above, the uncertainty of the DALY estimates might be a major drawback of the method.

This report shows that it is possible to derive DALYs for health loss due to a theoretical exposure to genotoxic drinking water contaminants. However, as the drinking water quality is very good in the

Netherlands, the exposure of consumers to these compounds through drinking water is very low compared to exposure through other routes e.g. the environment. Therefore, the theoretical loss in DALYs, which generally overestimates the real life situation, is very low in absolute (and relative) numbers. For other possible contaminants in drinking water, i.e. non-genotoxic carcinogens and other substances with a threshold effect, no toxic effects will occur in general at guideline value levels and thus no health loss will be expected upon lifetime exposure.

Future studies on health impact assessment of chemical drinking water contaminants may focus on metals present in drinking water. Recently, more epidemiological data and a meta-analysis have become available on the adverse health effect of exposure to low concentrations of metals in drinking water for inorganic arsenic [38, 39], manganese [40], and also for hexavalent chromium [41].Data from these studies may be suitable for a DALY calculation to estimate the human health impact of exposure to these contaminants at levels below current guidelines.

7 Literature

[1] Murray CJ, Lopez AD. Global mortality, disability, and the contribution of risk factors: Global Burden of Disease Study. Lancet. 1997 May 17;349(9063):1436-42.
[2] Havelaar AH, Melse, J.M. Quantifying public health risk in the WHO Guidelines for Drinking-Water Quality - a burden of disease approach. Bilthoven: RIVM; 2003.
[3] WHO. Global Burden of Disease 2004 update: disability weights for diseases and conditions. Geneva; 2004.
[4] Hoeymans N, Melse JM, Schoemaker CG. Gezondheid en determinanten - Deelrapport van de VTV 2010 Van Gezond naar Beter. Bilthoven: RIVM; 2010.
[5] Stouthard MEA, Essink-Bot M, Bonsel GJ. Disability weights for diseases - A modified protocol and results for a Western European region. European Journal of Public Health. 2000;10(1):24-30.
[6] WHO. Health-based targets. Geneva; 2010.
[7] RIVM. Nationaal Kompas Volksgezondheid - Sterfte, levensverwachting en DALY's. 2010 [cited 9 June 2010]; Available from: http://www.nationaalkompas.nl/gezondheid-en-ziekte/sterfte-levensverwachting-en-daly-s/
[8] Knol AB, Staatsen, B.A.M. Trends in the environmental burden of disease in the Netherlands 1980-2020. Bilthoven: RIVM; 2005.
[9] Schuur AG, Preller, L., ter Burg, W., Kramers, P.G.N., Kroese, E.D., van Engelen, J.G.M., Bausch-Goldbohm, R.A., van Kranen, H.J., van Raaij, M.T.M. Health impact assessment of policy measures for chemicals in non-food consumer products. Bilthoven: RIVM; 2008.
[10] Baars AJ, Pelgrom, S.M.G.J., Hoeymans, F.H.G.M., van Raaij, M.T.M. Gezondheidseffecten en ziektelast door blootstelling aan stoffen op de werkplek - een verkennend onderzoek. Bilthoven: RIVM; 2005.
[11] Baars AJ, van Leeuwen FXR, Kramers PGN. Harmful chemical constituents in our food. In: van Kreijl CF, Knaap, A.G.A.C., van Raaij, J.M.A., ed. *Our food, our health - healthy diet and safe food in the Netherlands*. Bilthoven: RIVM 2006:142-72.
[12] Havelaar AH, De Hollander AE, Teunis PF, Evers EG, Van Kranen HJ, Versteegh JF, et al. Balancing the risks and benefits of drinking water disinfection: disability adjusted life-years on the scale. Environ Health Perspect. 2000 Apr;108(4):315-21.
[13] WHO. Bromate in drinking-water Geneva: World Health Organization; 2005.
[14] von Gunten U. Ozonation of drinking water: part II. Disinfection and by-product formation in presence of bromide, iodide or chlorine. Water Res. 2003 Apr;37(7):1469-87.
[15] de Hollander AE, Melse JM, Lebret E, Kramers PG. An aggregate public health indicator to represent the impact of multiple environmental exposures. Epidemiology. 1999 Sep;10(5):606-17.
[16] Fewtrell L, Fuge R, Kay D. An estimation of the global burden of disease due to skin lesions caused by arsenic in drinking water. J Water Health. 2005 Jun;3(2):101-7.
[17] Ciketic S, Hayatbakhsh MR, Doran CM. Drinking water fluoridation in South East Queensland: a cost-effectiveness evaluation. Health Promot J Austr. 2010 Apr;21(1):51-6.
[18] Masago Y, Katayama H, Watanabe T, Haramoto E, Hashimoto A, Omura T, et al. Quantitative risk assessment of noroviruses in drinking water based on qualitative data in Japan. Environ Sci Technol. 2006 Dec 1;40(23):7428-33.
[19] Fewtrell L, Kay D. Health impact assessment for sustainable water management. London: IWA Publishing 2008.
[20] WHO. Guidelines for Drinking-water Quality. Geneva: WHO; 2008.
[21] WHO. 1,2-Dichloroethane in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2003.
[22] WHO. Trichloroethene in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2005.
[23] WHO. Acrylamide in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2003.
[24] Hogervorst JG, Baars BJ, Schouten LJ, Konings EJ, Goldbohm RA, van den Brandt PA. The carcinogenicity of dietary acrylamide intake: a comparative discussion of epidemiological and experimental animal research. Crit Rev Toxicol. 2010 Jul;40(6):485-512.

[25] WHO. Benzene in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2003.
[26] WHO. Polynuclear aromatic hydrocarbons in Drinking-water; 2003.
[27] IARC. Some Non-heterocyclic Polycyclic Aromatic Hydrocarbons and Some Related Exposures. Lyon, France: World Health Organization; 2010.
[28] WHO. N-Nitrosodimethylamine in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2008.
[29] Janssen PJCM, van Apeldoorn ME. Drinkwaternorm N-nitrosodimethylamine (NDMA). Bilthoven: RIVM; 2004.
[30] WHO. Vinyl chloride in Drinking-water - Background document for development of WHO Guidelines for Drinking-water Quality. Geneva; 2003.
[31] Crettaz P, Pennington D, Rhomberg L, Brand K, Jolliet O. Assessing human health response in life cycle assessment using ED10s and DALYs: part 1--Cancer effects. Risk Anal. 2002 Oct;22(5):931-46.
[32] US EPA. Guidelines for Carcinogen Risk Assessment. Washington, DC: US EPA; 2005.
[33] US EPA. US EPA Benchmark dose software (BMDS). 2011 [cited Jan-2011]; Available from: http://www.epa.gov/ncea/bmds/about.html
[34] Knol AB, Petersen AC, van der Sluijs JP, Lebret E. Dealing with uncertainties in environmental burden of disease assessment. Environ Health. 2009;8:21.
[35] Viscusi WK, Aldy JE. The value of a statistical life: A critical review of market estimates throughout the world. Journal of Risk and Uncertainty. 2003;27:5-76.
[36] van Wezel AP, Franken RO, Drissen E, Versluijs KC, van den Berg R. Societal cost-benefit analysis for soil remediation in The Netherlands. Integr Environ Assess Manag. 2008 Jan;4(1):61-74.
[37] Newsome R, Tran N, Paoli GM, Jaykus LA, Tompkin B, Miliotis M, et al. Development of a risk-ranking framework to evaluate potential high-threat microorganisms, toxins, and chemicals in food. J Food Sci. 2009 Mar;74(2):R39-45.
[38] Chu HA, Crawford-Brown DJ. Inorganic arsenic in drinking water and bladder cancer: a meta-analysis for dose-response assessment. Int J Environ Res Public Health. 2006 Dec;3(4):316-22.
[39] Gibb H, Haver C, Gaylor D, Ramasamy S, Lee JS, Lobdell D, et al. Utility of Recent Studies to Assess the National Research Council 2001 Estimates of Cancer Risk from Ingested Arsenic. Environ Health Perspect. 2011 Oct 27.
[40] Bouchard MF, Sauve S, Barbeau B, Legrand M, Brodeur ME, Bouffard T, et al. Intellectual Impairment in School-Age Children Exposed to Manganese from Drinking Water. Environ Health Perspect. 2011 Jan;119(1):138-43.
[41] California EPA. Public Health Goal for Hexavalent Chromium in Drinking Water. California: Pesticide and Environmental Toxicology Branch Office of Environmental Health Hazard Assessment California Environmental Protection Agency; 2010.

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