Analysis of Drinking Water treatment costs - with an Application to Groundwater Purification Valuation

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Academic editor: Alessandra La Notte

Abstract

Understanding the factors affecting drinking water production costs is crucial for choosing a cost-effective solution for public drinking water supply systems. An important determinant of water treatment costs is the purification of raw water. Despite water purification being a well-acknowledged ecosystem service, its monetary value has not been assessed much yet. We present the first study analysing the determinants of drinking water production costs and valuating groundwater purification in the Czech Republic. We tested the impact of the type of raw water, the amount of drinking water produced, electric power consumption and treatment technologies and chemicals. The results suggested that drinking water production from groundwater was cheaper than from surface water. Even though drinking water production from groundwater was cheaper than from surface water, the application of some technologies, for example, chlorine or manganese removal, increased the production cost. Hence groundwater production costs can exceed surface water production costs. The outcome of the regression was applied for the valuation of groundwater purification. The valuation was further used for the development of monetary drinking water accounts within the System of Environmental- Economic Accounting – Ecosystem Accounting.

Keywords

drinking water, groundwater, replacement cost method, treatment costs, System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA)

Introduction

Water treatment cost depends on raw water quality, treatment technologies, regulations, energy source and the amount of water treated (Plappally and Lienhard V 2013). Numerous studies find that improvement in source water quality decreases water treatment costs (Price et al. 2018). Due to the natural groundwater purification, groundwater is usually recognised as being cleaner than surface water (Schmidt et al. 2003) and, therefore, the treatment costs of groundwater are lower than surface water (Remme et al. 2015).

Water purification is probably amongst one of the most cited benefits provided by nature to humans, so-called ecosystem services (Vincent et al. 2016). Valuation of ecosystem services is important for improved decision-making, planning, monitoring, calculation of compensation value and national income accounting. However, the valuation faces many challenges, for example, linking the ecosystem structures and functions with the benefits and values (National Research Council 2005). The valuation for accounting faces additional challenges, for example, the definition of ecosystem services, their allocation to institutional sectors, the treatment of degradation and consistency with principles of the System of National Accounts (Edens and Hein 2013).

Despite there is a growing demand for water resources valuation (Edens and Graveland 2014) and the valuation of ecosystem services is crucial to improving decision-making (National Research Council 2005), research on water resources valuation is still rare (Vardon and Comisari 2013). Moreover, even though the groundwater purification service is well acknowledged (Herman et al. 2001, Bergkamp and Cross 2006), its monetary value has not yet been assessed to a great extent with a noteworthy exception of the valuation of groundwater purification service in the Netherlands (Remme et al. 2015). Mainly resource rent and replacement cost methods have been applied for the valuation of water-related ecosystem services (Møller et al. 2015). The resource rent method was applied to value marine fish provision in Finland (Lai et al. 2018) and water resources in the Netherlands (Edens and Graveland 2014). However, the authors concluded that the replacement cost method is more promising due to the frequent negative rents, which leads to undervalaution of water using the resource rent method (Edens and Graveland 2014).

The replacement cost method estimates the economic value of an ecosystem service by the cost of replacing the service with a man-made substitute (Barbier 2007). Applying this method, the value of groundwater purification can be estimated as the cost difference between the treatment of surface water and groundwater. An important advantage of the replacement cost method is that it can be used within the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA), as it is based on exchange values (UNSD 2021). The replacement cost method was applied to value the groundwater purification service and to set up SEEA EA accounts in the Netherlands (Remme et al. 2015, Horlings et al. 2020). However, the Dutch studies compared the average production costs of drinking water produced from groundwater and surface water only and did not

study other factors which are likely to affect the treatment costs, for example, treatment technologies or economies of scale.

Furthermore, the previous research on determinants of drinking water production costs focused mainly on North America and western Europe. In central Europe, there is a lack of water valuation studies, with a notable exception for the valuation of green water (Grammatikopoulou et al. 2020).

Therefore, we analysed drinking water production costs in a central European country - the Czech Republic. Next, we applied the results for the valuation of groundwater purification and development of the SEEA EA monetary drinking water accounts. To the best of our knowledge, this is the first study to investigate the determinants of drinking water production costs and to value groundwater in central Europe. Further, we believe that the SEEA EA monetary drinking water accounts have not been developed in central Europe yet.

Data

A database was obtained by merging data that the owners and operators of water supply systems mandatorily submit to the Ministry of Agriculture. The database contains one-year property and operating data (2018) for all water withdrawal points in the Czech Republic from which drinking water is commercially produced. To monitor compliance with pricing rules, the owners and operators of water supply and sewerage systems are obliged to submit a comparison of all items of the price calculation to the Ministry of Agriculture every year. The items are defined in the implementing decree to the Water Supply and Sewerage Act (MZE 2001a). Even though, according to the Water Framework Directive (European Parliament 2000), the price of water should cover full economic costs, drinking water price can reflect specified costs (eligible costs and reasonable profit) only in the Czech Republic (MZE 2001b). At the same time, it is possible to subsidise the price of drinking water (MZE 2020).

Drinking water is produced either from groundwater or from surface water in the Czech Republic. Groundwater is an important source of drinking water amounting to about 49% of the total drinking water production with a constant share during the last years (CSO 2019). A tiny fraction (5%) of drinking water is produced in managed infiltration of surface water in one location. In the studied year (2018), drinking water supply systems supplied water to 10.06 million people, i.e. 94.7% of the population were connected to the public drinking water supply system. The share of the population supplied by the water system has been stable in the long run and has remained above 92% since 2006 (CSO 2019). There is a large number of drinking water providers; mainly private enterprises, municipal companies and mixed owner-operator utilities.

Methodology

Model

A generic short-run cost function of a firm using an environmental input (Vincent et al. 2016 , Price and Heberling 2018) is:

$$C = f(WP, X, N, F, E) \quad (1)$$

where WP is the amount of output, X are firm-specific characteristics, for example, data on management, N is costs of non-environmental inputs, for example, labour, energy and treatment chemicals, F is costs of fixed factors and E is the quality of the natural capital.

As we investigated a unit change, we used a linear cost function instead of a logarithmic one which is used when elasticities are studied. Next, as we were particularly interested in the impact of the type of raw water on the unit production costs, we estimated the following linear cost function:

$$UCWC = \beta_0 + \beta_1 \ln WP + \beta_2 Power + \beta_3 Groundwater\_d + \beta_4 NoSludgeTreat + \beta_5 NoTreatment + b1\ TreatmentTechnology1 + b2\ TreatmentTechnology2 + \ldots\ldots + b30\ TreatmentTechnology30 + e \quad (2)$$

where *UCWC* is a unit cost without charges paid for water withdrawal; *WP* is the amount of water produced; *Power* is a unit consumption of electric power; *Groundwater_d, NoSludgeTreat and NoTreatment* is a dummy for a type of raw water, sludge treatment and no treatment, respectively. *TreatmentTechnology* are dummies for treatment technologies and chemicals. To account for non-linearities in output level as was shown in previous studies (Plappally and Lienhard V 2013), we used a natural logarithm of the amount of output (ln WP). *Groundwater_d* equalled 1 if the share of groundwater on total water production at abstraction point *a* was >= 0.5. The database contained information on 17 treatment technologies and 13 chemicals that were applied in water treatment companies. Descriptive statistics of all variables are presented in Table 1. Despite information on 30 treatment technologies and chemicals being included in the database, all these technologies could not be examined due to their infrequent usage. We used only the following 13 treatment technologies and chemicals with 5% and higher reported usage in the database: deacidification, demanganisation, filtration, chemical disinfection, chlorine, iron removal, no sludge treatment, no treatment, other aggregating agent, other technology, potassium permanganate, radon removal and sodium hypochlorite*[1].

We had no data for firm-specific characteristics (X), as well as for costs of fixed factors (F). Costs of non-environmental inputs (N) were represented by the consumption of electric power (*Power)* and sludge treatment (*NoSludgeTreat*). Quality of the natural capital (E) was represented by the type of raw water (*Groundwater_d),* no treatment (*NoTreatment) and* dummies for treatment technologies and chemicals (*TreatmentTechnology*).

Methodology

First, we calculated unit costs without charges. Since the water production cost included the charges paid for raw water and the charge rate was locally and type specific, we deducted them from the water production cost. We calculated the unit costs without charges for an abstraction point *a (UCWCa)* as follows:

$$UCWCa=(TPCa-SWa*CRSa-GWa*CRG)/WPa \quad (3)$$

where *TPCa* is total production costs for an abstraction point *a*, *SWa* is the amount of surface water abstracted at abstraction point *a*, *GWa* is the amount of groundwater abstracted at abstraction point *a*, *CRSa* is charge rate for surface water applied at abstraction point *a*, *CRG* is charge rate for groundwater and *WPa* is the amount of drinking water produced at abstraction point *a.*

Since the *TPCa* were not included in the database, we calculated them as:

$$TPCa=UCa*WPa \quad (4)$$

where UCa is the unit production costs (CZK/m^3). UCa was included in the database for each abstraction point. The drinking water producers calculate UCa as:

$$UCa=TPCa/IWa \quad (5)$$

where *TPCa* is the sum of material costs (raw water, chemicals, other material costs), energy costs, wages and salaries, other direct costs (depreciation; repair, rent and renovation of infrastructure assets), operating costs, financial costs and overhead costs. *IWa* is the amount of invoiced drinking water. We assumed that the amount of water produced equals the amount of invoiced water. The difference in the amount of water produced and invoiced can be either caused by storage or leakages. The companies store water to balance differences between the demand for water and its production. Hence, the stored water is distributed and invoiced in the next year similarly as stored water produced in the previous year was distributed in the studied year. Costs of leakages and the water leakage prevention costs are included in the total production costs.

Next, we cleaned the data in the database. We dropped observations with too low water production (the total amount of water produced < 0.01 km^3/year) and too low (1 m^3 < 0.5 CZK) or too high (1 m^3 > 50 CZK) UCWC (the thresholds for dropping observations were discussed at the Ministry of Agriculture - data provider). We supposed that too high or too low costs were entered wrongly. We also dropped three abstraction points where more than 50% of water production accounted for technological water. Next, we dropped five observations where infiltration was reported because infiltration is applied on one site only in the Czech Republic. Hence, the four observations were entered wrongly. After the data

cleaning, 3,253 observations remained (the total number of observations before the changes was 3,566).

Methodology - Water purification accounts according to SEEA-EA

First, the value of the groundwater purification (GPV) was calculated as:

GPV= WPG * ß3/ 26.444
(6)

where WPG is the amount of drinking water produced from groundwater (stated in the database) and ß3 (calculated in the egation 2) is the difference in production costs of drinking water from groundwater and surface water. The coefficient for *Groundwater_d* measures the average difference in production costs between groundwater and surface water when other factors (i.e. the amount of water produced, unit consumption of electric power, usage of treatment technologies and chemicals, sludge and no treatment), have the same levels (Wooldridge 2012). To calculate the impact in Euro, we applied an annual average exchange rate for the year 2020 (26.444 CZK/EUR) on the coefficient of *Groundwater_d* because the costs are stated in the Czech Crown (CZK) (CNB 2021).

Next, accounting tables according to the SEEA-EA were set up. Use tables record a flow of an ecosystem service to beneficiaries while supply tables depict which ecosystem types supply the ecosystem service (UNSD 2021). As the only users of the groundwater purification service are water treatment companies, the whole value of the service was allocated to this sector in the use table. Delineation of contributing areas to groundwater sources often requires detailed models (Johnson and Belitz 2009), but in absence of these models, circular buffer zones are used as contributing areas (Price and Heberling 2020). Due to a lack of models, a 5 km-wide buffer zone around each groundwater withdrawal point was used for the supply table compilation. First, we calculated a share of each ecosystem type on the total area of buffer zones. The value of groundwater purification for an ecosystem type was calculated as the total value of groundwater purification times the percentage share of the ecosystem type in all buffer zones. Ecosystems classification, defined in Mapping and Assessment of Ecosystem and their Services (MAES, level 2) (EEA 2016), were used in the supply table. Last but not least, the extent of ecosystem types in buffer zones was compared with the extent of the ecosystems in the whole Czech Republic to assess the importance of different ecosystems for water purification.

Results

First, we estimated a full model including all the explanatory variables, i.e. the ln *WP*, *Power*, *Groundwater_d*, *NoSludgeTreat*, *NoTreatment* and dummies on the 13 treatment technologies and chemicals. Since heteroscedasticity was detected (Breusch-Pagan test: F(16, 3236) = 5.35, Prob > F = 0.0000), robust errors were calculated for all specifications. The coefficients were statistically significant for the logarithm of the amount of water produced, electric power consumption and dummies for groundwater and some treatment

technologies and chemicals (demanganisation, chemical disinfection, chlorine, other aggregating agent and sodium hypochlorite).

Next, we dropped a variable with the lowest absolute value of the t-statistic (the following variables were gradually dropped: NoTreatment, NoSludgeTreat, PotassiumPermanganate, Filtration, RadonRemoval, Deacidification, OtherTechnology and IronRemoval) to simplify the model until significant variables only remained. In total, nine model specifications were tested and the results of all these specifications are reported in Suppl. material 1, columns 1-9. The same coefficients were significant in all tested model specifications.

Foremost, we found that the companies which produce drinking water mainly from groundwater experienced significantly lower production costs compared to the companies which produce drinking water mainly from surface water. The magnitude of this effect depended on the specification of the model and it ranged between 2.08 and 2.47. Hence, the drinking water production unit costs were 0.078 - 0.093 EUR lower if the drinking water was produced from groundwater.

Then, we confirmed economies of scale as the unit water production cost without charges significantly decreased with the logarithm of total water produced. This finding was significant at a level of 1% in all tested specifications. Next, the unit production costs slightly increased with the unit consumption of electric power (0.018-0.019 EUR/m^3).

Lastly, some treatment technologies and the application of some chemicals (demanganisation, chemical disinfection, chlorine, other aggregating agent and sodium hypochlorite) increased production costs. The highest impact occurred when sodium hypochlorite, chlorine and demanganisation were applied, which increased production unit costs by 0.179 – 0.181 EUR, 0.181-0.188 EUR and 0.102 – 0.150 EUR, respectively.

Water purification accounts according to SEEA-EA

The difference in production costs of drinking water from groundwater and surface water depended on the model specification. It ranged between 0.078 and 0.093 EUR/m^3. For the groundwater purification valuation, we used the cost difference of the model with significant variables only, which was 0.085 EUR/m^3 (the unit value of the service). The amount of drinking water produced from groundwater was 274,032 km^3 in 2018. Hence, the value of groundwater purification was 23.16 M EUR.

Next, monetary supply and use tables were set up (Tables 2, 3). Drinking water producers are the only user of the groundwater purification service (Use Table), while different ecosystems surround groundwater mining sites (Supply Table). The highest value of groundwater purification was attributed to cropland (41%). Woodland and forest accounted for 29% of the value of groundwater purification. Urban ecosystems, heathland and shrub and grassland accounted for 11%, 10% and 8%, respectively.

The Supply Table (Table 2) indicated that 41% of the buffer zones are covered with cropland, while 29% with forests, which is less than the national average i.e. 48% for cropland and 35% for forests (EEA 2020). At the same time, 11% and 10% of buffer zones were covered with urban ecosystems and heathland and shrub, respectively, while the national average is 6% and 0.02%, respectively. The difference for the rest of the ecosystems was smaller (Suppl. material 2). This indicated that groundwater mining sites are often located in urban areas. It should be noted that water can infiltrate elsewhere than in the buffer zones and, hence, different ecosystems can be responsible for water purification from those near abstraction points (and hence stated in the Supply Table). Hence, either detailed groundwater modelling is needed to attribute the exact ecosystems to groundwater purification or further research is needed on how to attribute the ecosystems to groundwater mining sites without groundwater modelling.

Discussion and Conclusion

It is necessary to understand the factors affecting drinking water treatment costs for designing cost-efficient public water systems. Moreover, the monetary valuation of the groundwater purification services, which have not been assessed to a great extent yet, would help to improve decision-making processes. This paper contributes to the existing literature by analysing the determinants of the drinking water production costs and estimating the value of the groundwater purification service in the Czech Republic.

The results showed that drinking water production from groundwater was cheaper than from surface water. However, some treatment technologies increased the treatment costs; hence, drinking water production from groundwater can be more expensive than from surface water if these technologies have to be applied. Next, we confirmed the economies of scale in drinking water production, which implies that centralised water treatment is more cost-efficient. Decreasing drinking water production costs with the logarithm of the amount of water treated were shown in previous studies (Ferro et al. 2011, Plappally and Lienhard V 2013). The economies of scale could be further tested using different specifications of the cost model, for example, translog or Cobb–Douglas, as has been studied previously (Ferro et al. 2011).

The estimated cost function was similar to a generic cost function, but we lack data for some explanatory variables, for example, data on firms´ characteristics and fixed factors. Next, we also had limited data on the costs of non-environmental inputs. As site-specific factors have the highest impact on the drinking water production costs (Plappally and Lienhard V 2013), the lack of these data probably caused a low R2. The problem of these missing data could be overcome using panel data as fixed effects control time-constant water treatment plant characteristics (Mulatu et al. 2021). However, if there are too many parameters in the fixed effects model and the fixed effects model would lead to an enormous loss of degrees of freedom, random effects models can be used instead (Baltagi 2005). Next, despite the database containing data on water quality (a water quality index), the index could not be used because the index was missing or stated wrongly in many observations.

The R-squared value for all specifications was relatively low (0.08). However, there is no assumption about a minimum level of R2 in linear regression models. Low R2 just means that a low amount of variation in the dependent variable is explained by the independent variables (Wooldridge 2012). In this case, the low R2 was caused by the site-specific factors which most impact the drinking water production costs (Plappally and Lienhard V 2013) and which were not included in the estimated cost function due to the lack of data.

Overall, the results suggested that drinking water production from groundwater was cheaper than from surface water. This is due to a usually better quality of groundwater relative to surface water (Schmidt et al. 2003, Warziniack et al. 2017) as a result of groundwater purification. Despite the great importance of ecosystem services connected with groundwater, these services are often neglected in decision-making since their value is difficult to calculate (Bergkamp and Cross 2006).

To assess the monetary value of the groundwater purification, we used regression results for the valuation of the groundwater purification service by the replacement cost method. The replacement cost method was applied for the valuation of the purification of surface water (La Notte et al. 2017) and groundwater (Remme et al. 2015, Horlings et al. 2020) in the Netherlands. The cost difference between surface water and groundwater detected in these studies was 0.40 EUR/m^3 (at 2010 prices in Remme et al. 2015) and 0.40 -0.49 EUR/m^3 (at 2012-2016 prices in Horlings et al. 2020).

The smaller cost difference in our study (0.078-0.093 EUR/m^3) was probably on account of controlling for other variables. The Dutch studies compared the average production costs only and failed to control for key variables, such as treatment technologies, electric power consumption and economies of scale. As a part of the cost difference can be probably attributed to these variables, the higher cost differences in the Dutch studies were probably caused by the omitted variables.

It should be emphasised that this approach measures the value of an extra-purification of groundwater relative to surface water only. The value of purification of surface water is not calculated even though its value is substantial (La Notte et al. 2017).

The valuation results were used for the development of monetary groundwater purification supply and use tables within the SEEA EA framework. A 5 km-wide buffer zone around each groundwater withdrawal point was used for the supply table compilation as no detailed models of groundwater flows were available. The buffer zone approach is often used in the absence of groundwater flow models (Price and Heberling 2020). However, it should be mentioned that water can infiltrate elsewhere than in the vicinity of the groundwater mining sites and so different ecosystems can be responsible for groundwater purification. Hence, either detailed groundwater modelling is needed to attribute the exact ecosystems to groundwater purification or further research is needed on how to attribute the ecosystems to groundwater mining sites without groundwater modelling.

Continued research is needed to improve estimated relationships. First, a panel data analysis would help to mitigate the problem of missing companies´ characteristics.

Likewise, more research is needed to quantify relationships between treatment costs and landscape characteristics as the links between ecosystem types and water quality are well established(Price and Heberling 2018, Lopes et al. 2019, Price and Heberling 2020).

Acknowledgements

We thank Věra Bogdanova (Ministry of Agriculture of the Czech Republic) and Ondřej Lípa (Ministry of Agriculture of the Czech Republic) for providing data and consultations.

Grant title

This research has been supported by the Czech Academy of Sciences, programme Strategy AV21 (project No. 21 “Záchrana a obnova krajiny”) and by project MAIA (Mapping and Assessment for Integrated ecosystem Accounting), EU call H2020-SC5-2018-1, Grant Agreement No. 817527.

Author contributions

Eva Horváthová: Conceptualisation, Data curation, Formal analysis, Methodology, Writing

Conflicts of interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Endnotes

*1 Excluded technologies include AC filtration, Activated powdered carbon, Al-based destabilising agent, gating agent, Biological filtration, Clarification, CO_2, Coagulation, Denitrification, Fe-based stabilising agent, Chlorine dioxide, Ion exchange, Lime hydrate, Membrane filtration, Ozone, Ozonisation, Sedimentation, Sodium carbon, Sodium hydroxide, Stabilisation and UV radiation.

Table 1.
Descriptive statistics.

Variable	Description	Obs	Mean	Std. Dev.	Min	Max
UCWC	Unit cost without charges (CZK/m^3)	3,253	12.73	9.77	0.52	49.9
WP	Total amount of water produced (km^3/year)	3,253	176.1	1,820	0.02	87,157
Power	Unit consumption of electric power (kWh/m^3 water produced)	3,253	0.71	1.36	0	43.64
Groundwater_d	Dummy v., = 1 if groundwater/total amount of water produced >= 0.5	3,253	0.96	0.2	0	1
NoSludgeTreat	Dummy v., = 1 if no sludge treatment	3,253	0.36	0.48	0	1
NoTreatment	Dummy v., = 1 if no water treatment is applied	3,253	0.55	0.5	0	1
Deacidification	Dummy v., = 1 if Deacidification by filtration or aeration applied	3,253	0.1	0.3	0	1
Demanganisation	Dummy v., = 1 if Demanganisation applied	3,253	0.105	0.306	0	1
Filtration	Dummy v., = 1 if Filtration applied	3,253	0.165	0.372	0	1
ChemDisinfection	Dummy v., = 1 if Chemical disinfection applied	3,253	0.378	0.485	0	1
Chlorine	Dummy v., = 1 if Chlorine applied	3,253	0.106	0.308	0	1
IronRemoval	Dummy v., = 1 if Iron removal applied	3,253	0.117	0.322	0	1
OtherAggregation	Dummy v., = 1 if Other aggregating agent applied	3,253	0.075	0.263	0	1
OtherTechnology	Dummy v., = 1 if Other technology applied	3,253	0.074	0.262	0	1
PotassiumPermangan	Dummy v., = 1 if Potassium permanganate applied	3,253	0.063	0.244	0	1
RadonRemoval	Dummy v., = 1 if Radon removal applied	3,253	0.079	0.27	0	1
SodiumHypochlorite	Dummy v., = 1 if Sodium hypochlorite applied	3,253	0.872	0.334	0	1

Table 2.

Supply monetary account for drinking water purification

		Ecosystem types								
	Measurement units	Cropland	Woodland and forest	Urban	Heathland and shrub	Grassland	Rivers and lakes	Wetlands	Sparsely vegetated areas	TOTAL SUPPLY
Ecosystem service										
Groundwater purification	K EUR/year	9,533	6,746	2,626	2,274	1,806	274	31	2	23,293
Total										23,293

Table 3.

Use monetary account for drinking water purification

		Institutional sector								
	Measurement units	agriculture	forestry	fisheries	mining and quarrying	manufacturing	construction	electricity, gas supply	water collection, treatment, supply	other indust
Ecosystem service										
Groundwater purification	K EUR/year								23,293	
Total									23,293	

Supplementary materials

Suppl. material 1: Regression results

Authors: Horváthová
Data type: Results
Brief description: Regression results. Dependent variable: UCWC (the unit costs without charges)
Download file (2.50 kb)

Suppl. material 2: Ecosystem types

Authors: Horváthová
Data type: Results
Brief description: Ecosystem types (%) in groundwater buffer zones (Supply account) and the whole Czech Republic.
Download file (15.49 kb)