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ASTA - a method for multi-criteria evaluation of water supply technologies to Assess the most
SusTainable Alternative for Copenhagen

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Abstract

Utilities in larger cities have to make complex decisions planning future investments in urban water infrastructure. Changes are driven by physical water stress or political targets for environmental water flows e.g. through the implementation of the European water framework directive. To include these environmental, economic and social sustainability dimensions we introduce a novel multi-criteria assessment method for evaluation of water supply technologies. The method is presented and demonstrated for four alternatives for water supply based on groundwater, rain- & stormwater or seawater developed for augmenting Copenhagen's current groundwater based water supply. To identify the most sustainable technology, we applied rank order distribution weights to a multi-criteria decision analysis to combine the impact assessments of environment, economy and society. The three dimensions were assessed using 1) life-cycle assessment, 2) cost calculations taking operation and maintenance into account and 3) the multi-criteria decision analysis method

22 Analytical hierarchy process. Specialists conducted the life-cycle assessment and cost calculations
23 and the multi-criteria decision analyses were based on a stakeholder workshop gathering
24 stakeholders relevant for the specific case. The workshop reached consensus on three sets of ranked
25 criteria. Each set represented stakeholder perspectives with first priority given to one of the three
26 sustainability dimensions or categories. The workshop reached consensus and when the highest
27 weight was assigned to the environmental dimension of sustainability then the alternative of ‘Rain-
28 & stormwater harvesting’ was the most sustainable water supply technology; when the highest
29 weight was assigned to the economy or society dimensions then an alternative with ‘Groundwater
30 abstraction extended with compensating actions’ was considered the most sustainable water supply
31 technology. Across all three sets of ranked weights, the establishment of new well fields is
32 considered the least sustainable alternative.

33 **Keywords:** Analytical hierarchy process; Desalination; Economic assessment; Freshwater
34 withdrawal impact; Groundwater abstraction; Life-cycle assessment; Multi-criteria decision
35 analysis; Rain- and stormwater harvesting; Ranked order distribution; Water supply

36 **1 Introduction**

37 The impact of withdrawing water is high on the agenda both regarding a worldwide focus on the
38 limited freshwater availability (Alcamo & Gallopín, 2009; European Environment Agency, 2012),
39 legislation (European Union, 2000) and the sustainable development goals (UN, 2015) emphasizing
40 the importance of protecting freshwater environments and ecosystems. The European water
41 framework directive (EU-WFD) is implemented in the EU-Member states by the national river
42 basin management plans which among other parameters regulate the water flow requirements for
43 water courses and the available amount of water in each freshwater compartment, including
44 groundwater bodies. In Denmark the implementation of the EU-WFD has revealed that
45 groundwater is not as abundant a resource as often assumed (European Environment Agency, 2007)
46 since the river basin management plans for Denmark require that 65% of the renewable
47 groundwater resource should be allocated to the freshwater environments (Danish Nature Agency,
48 2011).

49 In Europe on average 70% of the drinking water is produced from groundwater (Navarrete *et al.*,
50 2008) and in Denmark groundwater is currently the only source used for centralized water supply
51 and only very few local rainwater harvesting systems exist (Rygaard *et al.*, 2009). Therefore, the
52 implementation of the EU-WFD has forced the water utility in Copenhagen, HOFOR, to explore
53 new approaches to maintain abstraction licenses or new water resources for water production in
54 order to meet the water demand of the Capital City, Copenhagen. Since water production in
55 Copenhagen today solely relies on groundwater, the impacts on the groundwater resources and
56 natural environments such as water flow in watercourses has to be included in environmental
57 evaluations of alternative water resources.

58 Besides groundwater resources, other criteria are important to include in the decision making
59 process of how to identify the most suitable or, as in our case, the most sustainable water supply
60 alternative for the City.

61 The term “sustainable development” is often quoted from the Brundtland Commission (WCED,
62 1987) as: “development that meets the needs of the present generation without compromising the
63 ability of future generations to meet their own needs”. In 1992 this definition of sustainable
64 development was concretized a step further as a balance of three dimensions: environmental
65 protection, economic growth, and social development (UNEP, 1992). Therefore, not only the
66 impact on the water courses has to be considered but criteria representing these three dimensions –
67 environment, economy and society – also have to be included in the development of decision
68 support. This can be achieved by life-cycle assessment (LCA), cost-benefit analysis (CBA) and
69 multi-criteria decision analysis (MCDA) with involvement of central stakeholders. The goal for our
70 investigation was to develop a decision support system which incorporates criteria for all three
71 sustainability dimensions and determines the trade-off between various criteria. Thus, providing the
72 decision maker with a decision support material where weighting and trade offs are carried out and
73 are not left for manual subjective judgement. The resulting decision support system “Assessing the
74 most Sustainable Alternative” (ASTA) thus integrates LCA, CBA and MCDA into one joint
75 decision support tool.

76 Multi-criteria decision analysis (MCDA) supports decision making in the choice between several
77 options or cases based on evaluations involving several different criteria. MCDA has been applied
78 in many cases within water management as documented by Hajkowicz & Collins (2007) who listed
79 113 studies on MCDA in water management published since 1973. The purpose of using MCDA in
80 water management are various, e.g. policy evaluation, strategic planning, infrastructure selection.

81 Within the water sector MCDA has thus been used to identify the optimal solution by a) elicit
82 scores to criteria and b) determine the capacity for trade-offs between criteria: 1) Some MCDA
83 methods are applicable for eliciting scores for alternative water management cases based upon pre-
84 defined criteria, if other more quantitative evaluation methods such as LCA or CBA are not within
85 hand (Jaber & Mohsen, 2001; Makropoulos *et al.*, 2008). 2) Other MCDA methods are designed to
86 assign weights to criteria based on their relative importance to central stakeholders (Goodwin &
87 Wright, 2009; Lai *et al.*, 2008; Rowley *et al.*, 2012). For instance Sombekke *et al.*, 1997) used
88 MCDA to combine the results of an LCA with other criteria (water quality and public health,
89 reliability, landscape, economy, etc.) when choosing between two types of water treatment for
90 reducing water hardness at the waterworks (central softening). MCDA methods are also
91 recommended for combining multiple criteria in the framework for decision support systems aimed
92 at making a sustainable decision as described in the work of Lundie *et al.* (2006) and Halog &
93 Manik (2011).

94 We developed a unique integration of quantitative evaluation tools (LCA, Freshwater Impact
95 Assessment and Cost Assessment) and more qualitative assessment of societal impacts. At a
96 stakeholder workshop we used the Analytical Hierarchy Process (AHP) (Saaty, 2006) to convert the
97 assessment of the social dimension into quantitative scores. The combining of the sustainability
98 dimensions, e.g. in a DSS is necessary to identify the optimal and most sustainable solution in a
99 study. The same approach is found in studies planning sustainable community water systems when
100 urbanization is increasing (Schoen *et al.*, 2017; Rygaard *et al.*, 2014) also aiming at combining
101 various criteria or metrics. In our case, we used the above-mentioned evaluation tools and integrated
102 the assessments in a multi-criteria workshop with representatives from a broad range of
103 stakeholders with interest in urban water supply. To acknowledge different preferences, the

assessment method was designed to assign individual stakeholder weights to qualitative criteria as well as the weighting between the three sustainability dimensions: environment, economy and societal impacts. Our method was demonstrated in a test case built on four suggested alternatives for water supply to Copenhagen, Denmark.

2 Material and methods

2.1 Study area and alternatives

Four water supply alternatives have been identified for Copenhagen that can, either alone or in combination with the existing groundwater abstraction (A0), constitute Copenhagen's future water supply fulfilling the EU-WFD requirements. The present water supply method and the alternatives are (Figure 1): A0: 'Base alternative' (the current situation), A1: 'Rain- & stormwater harvesting', A2: 'Compensating actions', A3: 'New well fields', A4: 'Desalination'. A list of the alternatives' life-cycle inventory is found in Supplementary material.

2.1.1 Alternative A0: Base Alternative (the current situation)

A groundwater volume of approximately 50 million m³ is annually abstracted to supply the area of Greater Copenhagen (population of 1.28 million) with drinking water. The water is abstracted from groundwater sources mainly located outside the city and requires only treatment in terms of aeration and rapid sand filtration before distribution. The water abstraction, treatment and distribution consume as little as 0.27 kWh per m³ drinking water. The groundwater originates from chalk aquifers and has a hardness of 362 mg/L as CaCO₃ categorized as very hard drinking water (US Geological Survey, 2012). This high hardness causes indirect environmental impacts in the households when water is consumed (Godskesen *et al.*, 2012) and these impacts are included in the comparison with the alternatives with a lower water hardness leading to lower environmental

126 impacts (A1 and A4). After use wastewater is transported via combined sewers to the municipal
127 wastewater treatment plants where it is treated before discharge to the Sea (Øresund).

128 **2.1.2 Alternative A1: Rain- & stormwater harvesting**

129 Rain- and stormwater is considered harvested from an urban area of 68,500 m² (where roof area is
130 20,200 m² and main road area is 8,500 m² the rest is primarily smaller roads, pavements and green
131 areas) populated by 1,000 residents and 200 employees. Rainwater is collected from the roofs and
132 led to an underground basin (750 m³). Stormwater from the main road is collected in large pipes
133 (diameter 1,000 mm) and led to a basin with a clarifier and pumping station controlling the flow.
134 The clarifier separates oils from the water before it passes through a dual porosity filter where the
135 stormwater by gravity flows through a filter of CaCO₃ particles to adsorb and remove suspended
136 solids, heavy metals and PAHs (Jensen, 2009). Afterwards the treated stormwater is mixed with
137 rainwater and stored in a basin. The water is UV-treated prior to distribution back to the residential
138 and office buildings from where the rainwater was originally collected. After treatment the water
139 hardness is 145 mg/L as CaCO₃ (Jensen, 2009). The water is considered of non-potable quality and
140 is used for toilet flushing and clothes washing. The area has combined sewers, which is the typical
141 situation in most parts of Copenhagen, and the reduction of the rain- and stormwater gives a
142 significant environmental advantage to A1 since electricity consumption for transport and treatment
143 of wastewater is reduced. The scale of the A1 alternative is smaller than the other alternatives as it
144 covers a smaller part of the city but could be expanded to the entire city including site specific
145 changes dependent on the architectural structure of the areas in the city. The environmental and
146 economic evaluations are calculated per m³ delivered water making the evaluations comparable
147 even though the scales differ.

148 **2.1.3 Alternative A2: Compensating actions**

149 ‘Compensating actions’ covers various initiatives implemented to meet the water flows in
150 watercourses required as consequence of the implementation of the EU-WFD while maintaining the
151 current groundwater abstraction. We considered compensating actions such as a) pumping of
152 590,000 m³ of groundwater and water from lakes per year to watercourses with low water flow and
153 b) re-establishment of 18 hectares of wetlands from agricultural land (Supplementary material). The
154 extent of compensating actions is based on the Danish EPA’s guidelines to retain permissions for
155 groundwater abstraction to meet Copenhagen’s water demand. Besides the various compensating
156 actions the alternative (A2) included all processes in the base alternative (A0).

157 **2.1.4 Alternative A3: New well fields**

158 The new well fields alternative is also equivalent to the base alternative but added a 20 km long
159 pipeline from well fields to the waterworks while the distance is 5 km in the A0 alternative. The
160 longer distance means increased energy consumption but new well fields 25 km from the
161 waterworks are assumed to meet the requirements of the EU-WFD.

162 **2.1.5 Alternative A4: Desalination**

163 Copenhagen is situated at the entrance to the brackish Baltic Sea (Øresund) and desalination of
164 seawater is an option. The treatment plant is assumed to be located 5 km south of the city. The
165 processes of the plant consist of: mechanical filtration (150 µm) to remove large particles; addition
166 of a coagulant; pH adjustment; ultra-filtration where 10% of the water is lost and returned to
167 Øresund after extraction of dry material; addition of anti-scaling; reverse osmosis desalination;
168 remineralization; and finally UV-treatment. The water hardness is designed to be 108 mg/L as
169 CaCO₃ when distributed (Rygaard, 2010).

170 **2.2 A model to assess the most SusTainable Alternative (ASTA)**

171 ASTA DSS was constructed to assist the decision maker in choosing the most sustainable
172 alternative within a given range of alternative solutions to a predefined problem. ASTA DSS
173 (Figure 2) divides the sustainability assessment into a hierarchy:

- 174 • First level has the 3 sustainability dimensions (environment, economy and society);
- 175 • Second level has in total 6 criteria within the dimensions
- 176 • Third level holds in total 13 indicators against which all alternatives are evaluated.

177 The three levels (dimensions, criteria and indicators) were chosen to break down the assessment
178 into indicators relevant to evaluate. For instance, for the environment dimension the criteria were
179 environmental, toxicity and resource impacts which are assessed through the impact categories of
180 the LCA (e.g. global warming potential, acidification, nutrient enrichment). The result is presented
181 with a total score and a bar chart showing the contribution from the 3 sustainability dimensions to
182 the total score. To make the decision transparent the scores can also be presented at the criteria level
183 (level 2) underlying each of the sustainability dimensions (level 1).

184 ASTA is based on 3 steps explained in the following.

185 **2.3 Step 1: Quantifying impacts at indicator level**

186 The impacts on the 3 dimensions of sustainability were quantified for the 13 indicators using
187 available tools for each sustainability dimension. Environmental impacts and economy were
188 quantified using life-cycle assessment and cost calculations. Societal indicators were quantified
189 from qualitative judgments by the use of an Analytical hierarchy process (AHP).

190 **2.3.1 Environmental indicators quantified by LCA**

191 The assessment of the sustainability dimension ‘Environment’ was assessed by the life-cycle
192 assessment (LCA) tool where impacts on the environment (global warming, acidification, nutrient
193 enrichment), on toxicity (eco toxicity via water and on human toxicity via water and soil) and
194 resources are evaluated taking a life-cycle perspective on the alternatives. Inputs and emissions are
195 included from the phases of extraction of raw materials through assembly, use and end-of-life
196 treatment of all materials (Wenzel *et al.*, 1997). The LCA of the base case and the 4 alternatives
197 was performed according to the ISO 14044 standard procedure (ISO, 2006) with the GaBi 4.4
198 software delivered by PE International. The database from PE International was primarily used and
199 when found insufficient the Eco-Invent database was used. Impacts were assessed by the EDIP
200 1997 method which is a standardized midpoint LCA method initially developed for the
201 environmental development of industrial products (Wenzel *et al.*, 1997) but also applicable for
202 services such as drinking water supply (Godskesen *et al.*, 2011). The EDIP method shares
203 dominating many similarities with other life-cycle impact assessment (LCIS) methods e.g. ReCiPe,
204 ILCD, TRACI 1.0 and 2, CML, but also some differences especially in the toxicity categories
205 (Hauschild *et al.*, 2018; Dreyer *et al.*, 2003). As we use the LCA for comparison among alternative
206 technologies for water supply we find the EDIP method applicable. A strength of the EDIP-method
207 in our case is that the method is developed for the region of Europe. The normalized results of the
208 midpoint method for Europe were calculated and used in the decision process (Godskesen *et al.*,
209 2013).

210 In water production, water is the dominant resource consumed. In order to model the impacts of
211 abstracting freshwater we modified and applied a method originally aimed at assessing freshwater
212 withdrawal impacts (FWI) of industry on a regional scale (Lévová & Hauschild, 2011) by

213 converting to a local scale and basing the calculations on data on groundwater volumes (utilizable
214 volume and environmental freshwater requirements) from national regulations implementing the
215 EU-WFD (Godskesen *et al.*, 2013). The FWI assessments of the 4 alternatives were used as a
216 measure for the criterium ‘Resource impacts’.

217 The functional unit in the LCA was production of water which fulfilled the EU-WFD’s water flow
218 requirements for water courses where freshwater was withdrawn and replacing 1 m³ of potable
219 drinking water as produced today. The produced water could be potable or non-potable depending
220 on the use of the drinking water that it replaces.

221 **2.3.2 Economy indicator quantified by utility costs**

222 In the ASTA DSS the evaluation of economy is intended to be based on a cost-benefit analysis
223 (CBA) including costs of the utility regarding investment, operation and maintenance as well as
224 costs or benefits located in the society (Pearce *et al.*, 2006) thereby making the system boundaries
225 equivalent to the LCA. However, due to limited access to data and to avoid additional uncertainty a
226 full cost-benefit analysis was not applied here. Instead, a partial life cycle cost analysis with focus
227 on the direct costs for the utility was conducted. This provided a means of combining investment
228 costs with ongoing costs into an annualized cost allowing for comparison across alternatives. Data
229 was based on the economic evaluation of projects similar to our alternatives carried out internally in
230 HOFOR (HOFOR, 2012). Thus, the system boundaries differs from the LCA where the effects in
231 the freshwater environments, at the consumers and wastewater treatment plant also were included.
232 The costs were calculated per m³ delivered making the alternatives comparable even though they do
233 not cover the same scale, e.g. supplying same amount of residents with water.

234 **2.3.3 Societal indicators quantified by stakeholder workshop**

235 The LCA and economic evaluation were carried out by a specialist and resulted in direct
236 quantifications of impacts. Assessment of sustainability in the social dimension is inevitably
237 influenced by subjective judgments and statements. To convert the assessment of the social
238 dimension into quantitative scores, the indicators of the social dimension were assessed by
239 stakeholders at a workshop using the Analytical Hierarchy Process (AHP) (Saaty, 2006). The
240 workshop had 17 participants all related to the urban water supply (Table 1).

241 The 5 indicators in the social dimension were:

- 242 1) ‘Acceptance of & reliance on technology’, i.e. the assumed public acceptance of the
243 alternatives and the public confidence in the proposed technology implementation. In other
244 words: a measure of the public trust in the system
- 245 2) ‘Aesthetics’, which cover interpretation of the visual appearance of the system as well as
246 perceived aesthetic acceptance
- 247 3) ‘Tourism & contribution to water hub’, where the assumed impact on tourism business was
248 evaluated alongside the system’s ability to attract international attention to local innovation
249 within water technology
- 250 4) ‘Political independency, i.e. the alternative’s potential for increasing water self-sufficiency
251 in the area and reducing dependency on regulators outside the municipality
- 252 5) ‘Resilience’, which covers the robustness, flexibility and adaptive capability of the system
253 towards unpredictable or unforeseen events and developments, for example power outage,
254 storms and climate change. There is no standard resilience assessment (Xue *et al.* (2015) but
255 the stakeholders agreed on this explanation which they agreed on at the workshop.

Indicators 1 to 3 belong to the criterion ‘Customer values’ and indicator 4 and 5 belong to criterion ‘Applicability & demand’.

In AHP, preferences between n alternatives were determined by pair-wise comparisons for one indicator at a time resulting in a score x_{ij} measuring the importance or dominance of alternative i over alternative j . The comparison score was determined using the verbal value scale (Saaty, 2006) consisting of 5 verbal evaluations of importance or dominance and their intermediates (Figure 3). For each pair-wise comparison the stakeholders agreed on a verbal score describing the dominance or importance of one alternative over the other and assigned the associated value as the score x_{ij} . The scores were inserted in a decision matrix of the AHP method:

$indicator_x$	$Alternative_1$	$Alternative_2$	$\dots$	$Alternative_n$
$Alternative_1$	1	x_{12}	$\dots$	x_{1n}
$Alternative_2$	x_{21}	1	$\dots$	x_{2n}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$Alternative_n$	x_{n1}	x_{n2}	$\dots$	1

The relative score of each alternative was found by calculating the geometric mean,

$$G_i = \sqrt[n]{x_{i1} \cdot x_{i2} \cdot \dots \cdot x_{in}}, \text{ of each row in the decision matrix.}$$

To evaluate the consistence of the AHP method, it provides an inconsistency index =

$\frac{\text{average ratio} - n}{n-1}$ for each set of judgments (set of all scores in a decision matrix). n is the number of alternatives and the *average ratio* is the average of the sums of each row in the decision matrix divided by the weight of the criteria (Goodwin & Wright, 2009). A low index indicates consistency of the judgments of each alternative, however a low index is not the goal of the process. As a rule of thumb the inconsistency index should be less than 0.1 when comparing 4 or more alternatives

274 (Goodwin & Wright, 2009). If the index was above 0.1 the judgments were reassessed and adjusted
275 accordingly if agreed upon among the stakeholders.

276 **2.4 Step 2: Weighting of indicators, criteria and sustainability dimensions**

277 In the second step each indicator's relative contribution to each criterion was calculated as the sum
278 of weighted indicator scores. Then weights were assigned to the individual criteria and
279 sustainability dimensions in a stakeholder workshop.

280 **2.4.1 Weighting of indicators**

281 For indicators in the society dimension, the importance was assumed to be equal and they were
282 weighted equally. The environmental indicators were weighted according to the LCA methodology
283 (Wenzel *et al.*, 1997), and criteria with just 1 indicator per criteria, i.e. economy and resource
284 impacts, only weighting of indicators was needed.

285 **2.4.2 Weighting of criteria and sustainability dimensions in the stakeholder workshop**

286 The stakeholder workshop scoring of societal indicators also assessed the stakeholders' views on
287 the importance of sustainability dimensions and underlying criteria. The weights of the
288 sustainability dimensions and criteria were determined by the ranked order distribution (ROD)
289 method (Roberts & Goodwin, 2002) . Prior to the workshop we had predefined 3 sets of rank
290 ordering where respectively environment, economy or society was given the highest rank. The
291 stakeholders were asked to form 3 groups matching their first priority of sustainability dimension
292 and were given 20 minutes to negotiate an agreement on the rank of the remaining 2 dimensions
293 and the rank of each criterion within each of the 3 dimensions. The predefined sets of rank ordering
294 made it easier to reach the final rank order. Finally, ROD weights (Table 2) were assigned to each
295 sustainability dimension or criterion as suggested for this type of rank ordering (Roberts &
296 Goodwin, 2002).

297 **2.5 Step 3: Combining results of indicators with the additive model**

298 In the third step, the results of dimensions and criteria are combined using an additive model based
299 on weighted sums. This procedure leads to the final evaluation of the proposed alternatives.

300 The indicator results in the ASTA DSS are reported on different scales and in different metrics. To
301 facilitate their comparison, we introduced an internal normalization step where each indicator result
302 or score for each alternative was divided by the sum for this indicator across all 4 alternatives. The
303 normalization step converted the results to a common scale for all indicators of the ASTA DSS and
304 lead to scores expressed as a proportion of the sum of all scores on a specific criterion and is a
305 commonly used procedure for normalization in MCDA (Rowley *et al.*, 2012). Hereby we
306 considered the study on a local scale consisting of the 4 involved alternatives.

307 ASTA DSS is built on the principles of an additive weighted sum model. By adding the
308 contribution from each indicator for each alternative we obtain the total score (Goodwin & Wright,
309 2009) of the alternatives. This means that the next step was to multiply each alternative's
310 normalized scores by the weights of the indicators and summed to arrive at the score for each
311 criterion. Then the criteria scores were multiplied by the weights elicited for the criteria and
312 summed to give the score for each sustainability dimension and finally these scores were multiplied
313 by the weights for the sustainability dimensions and summed to arrive at an overall sustainability
314 score for each alternative:

315
$$\text{Total score} = \sum_{i=1}^n (w_i s_i(a))$$

316 where w is the weight and s is the score of the i 'th sustainability dimension, criteria or indicator of
317 alternative a . The Total score is an addition of the scores ($w_i \bullet s_i$) of the indicators, criteria and
318 sustainability dimensions.

319 **2.5.1 Inverting negative impacts**

320 A high total score in ASTA DSS means a preferable performance. To integrate all scores of
321 indicators, the reciprocal values of the LCA weighted impacts, resource impacts and costs were
322 normalized so that a high value in the LCA, FWI or costs calculations resulted in a low contribution
323 to the total score of the ASTA DSS.

324 **3 Results & Discussion**

325 **3.1 Environment**

326 For the environment dimension the alternative A1 ‘Rain- & stormwater harvesting’ achieves the
327 highest score within all 3 criteria: total environmental impacts; total toxicity impacts; and resource
328 impacts (FWI) (Table 3). A1 has the highest scores of total environmental (0.369) and toxicity
329 impacts (0.356) due to the prevention of the rain being discharged directly into the combined
330 sewers, and avoiding its treatment at the wastewater treatment plant. A1 also obtains a high score
331 due to the lower hardness of the rain- and stormwater which has positive effects in the households
332 such as longer service life of washing machines and toilets, and lower electricity and laundry
333 detergent consumption when washing clothes (Godskesen *et al.*, 2012). The alternative A4
334 ‘Desalination of seawater’ obtained the lowest score for environmental (0.151) and toxicity impacts
335 (0.168) due to the high energy requirements of the desalination processes. The difference between
336 A4 and the groundwater based alternatives A2 and A3 was relatively low, mainly due to the
337 positive effects of reduced hardness of the desalinated water. For the groundwater based
338 alternatives, the scores of total environmental and toxicity impacts were between A1 and A4.
339 However, a previous study showed that water production from groundwater was environmentally
340 preferable compared to other technologies for drinking water production such as membrane
341 treatment of lake water, artificial recharge of groundwater or desalination of seawater (e.g. as in
342 A4) (Godskesen *et al.*, 2011). At the indicator level A4 ‘Desalination’ performed better than the
343 groundwater based alternatives A2 and A3 for the indicators ecotoxicity water and human toxicity
344 water, which can be explained by reduced effects of hardness e.g. lower consumption of laundry
345 detergent and increased service life of domestic appliances leading to lower consumption of
346 materials.

347 The A1 and A4 alternatives both obtained much higher scores on FWI (0.636; 0.362) than the
348 alternatives with groundwater abstraction (0.001). The use of rainfall or seawater scored high (A1
349 and A4) on this indicator in contrast to the groundwater based water supplies (A2 and A3) since
350 these rely on the freshwater resource considered of high value and in scarcity in some regions
351 (European Environment Agency, 2012; Gleick, 2009).

352 **3.2 Economy**

353 Cost was estimated for investment, operation and maintenance and expressed in Euro per m³ water
354 delivered to the household. A1 Rain & stormwater harvesting were markedly costlier at 3.8 €/m³
355 than the other alternatives ranging from 0.4 to 1.1 €/m³ (Figure 4). The high cost of rain and
356 stormwater harvesting is mainly due to high investment costs in relation to a relatively low amount
357 of produced water. The normalized scores of the assessment of the economy showed that alternative
358 A2 Compensating actions is preferable (0.480) followed by A3 New well fields (0.286) and A4
359 Desalination (0.182) (**Table 3**).

360 **3.3 Society**

361 Selected results are shown in the following. Complete dataset from the stakeholder workshop is
362 available from the corresponding author.

363 **3.3.1 Society – indicator level**

364 As an example of the AHP method we present the detailed result of indicator 1) ‘Acceptance &
365 reliance on technology’ within the criterion ‘Customer values’. The 17 stakeholders reached
366 consensus on A2 ‘Compensating actions’ had a *strong* to *very strong* importance over A1 ‘Rain &
367 stormwater harvesting’. This verbal score results in a numerical value of 6, which implies that A2
368 has a 0.17 importance over A1. All the alternatives were judged against each other and the
369 geometric mean and normalized scores were calculated (Table 4). The procedure resulted in

370 geometric means 0.34 for A1 and 3.22 for A2, and normalized scores of 0.059 for A1 and 0.557 A2
371 for the indicator 1) ‘Acceptance & reliance on technology’. These results implied that A2
372 ‘Compensating actions’ is seen as the most sustainable alternative considering the indicator 1)
373 ‘Acceptance & reliance on ‘technology’. The procedure was similar for the 4 remaining social
374 indicators.

375 **3.3.2 Society – criteria level**

376 For the criterion ‘Customer values’, alternative A2 ‘Compensating actions’ obtained the highest
377 score on all 3 indicators (**Table 3**: 0.557; 0.564; 0.375). For the indicator ‘tourism & contribution to
378 water hub’, stakeholders expressed that groundwater abstraction such as compensating actions were
379 something that we in Denmark have experience and knowledge on and therefore have a strong
380 potential for development and innovation through compensating actions. The desalination (A4) and
381 rain- & stormwater (A1) alternatives got generally low scores on the indicators under the “customer
382 values” criterion except for ‘Tourism & contribution to water hub’ where A1 obtains the highest
383 score together with A2 (0.375).

384 The A4 alternative got high scores on the criterion ‘Applicability & demand’, in particular because
385 this alternative is independent from other authorities of the area such as municipalities who also
386 have an interest in the area’s groundwater (0.406 on the political independency indicator) and
387 shows strong resilience regardless of e.g. predicted drought effects of global warming (0.504 on the
388 resilience indicator).

389 The inconsistency index was below 0.1 for all indicators, except 2) ‘Aesthetics’, where the
390 inconsistency ratio was 0.21. This indicates a general consistency of the society indicator judgments
391 across the alternatives, except for ‘Aesthetics’, which may be explained by a possible ambiguous
392 perception of that specific indicator.

393 **3.4 Assigning weights to sustainability categories and criteria**

394 Each of the three stakeholder teams had a set of rank ordering and weights for the sustainability
395 dimensions and criteria. Set 1 represented the stakeholder team assigning the highest weight to the
396 sustainability dimension environment; Set 2 to economy; and set 3 to society (**Table 5**). ROD
397 weights (Table 2) were assigned to the 3 dimensions with the most important dimension receiving
398 the weight 0.5232, the second 0.3240 and the third 0.1528.

399 It is noteworthy that regardless the set of weights applied, freshwater withdrawal impact was
400 identified as the most important among the environmental criteria (Table 5). This demonstrated the
401 high perceived importance of freshwater consumption and is in agreement with the focus of
402 politicians and researchers as expressed today in policy reports (European Environment Agency,
403 2012), European regulations (European Union, 2000) and the strong research interest in integrating
404 freshwater consumption into the LCA methodology (Pfister et al., 2009; Tendall et al., 2013).

405 **3.5 The ASTA-model**

406 **3.5.1 Total score results with 3 sets of weights**

407 We designed and carried out the ASTA-DSS including choosing the criteria in collaboration with
408 the utility. The sustainability criteria in this study were chosen to support the evaluation of
409 alternatives for planning future water supply systems for Copenhagen. The criteria are found
410 equivalent to other sustainability assessments based on various metrics (Xue *et al.*, 2015; Rygaard
411 *et al.*, 2014).

412 With the weighting of all indicators, criteria and dimensions in place, the total sustainability score
413 of each alternative was calculated with each of the 3 sets of weights. Figure 5 shows the results
414 subdivided on the underlying sustainability criteria. When the highest weight was assigned to
415 environment the alternative A1 ‘Rain- & stormwater harvesting’ obtained the highest total score

416 (0.34) and was the most sustainable alternative according to the ASTA-model. However, at the
417 stakeholder workshop many stakeholders expressed concerns regarding risk management,
418 especially when it comes to people's health and the costs of A1 'Rain- & stormwater'. A risk
419 assessment of the alternatives could be a way to address the concerns for health and risk
420 management in the alternatives, for example related to cross connections or risk of pollutants
421 entering the potable water system, but this was not included here.

422 A1 was followed by A4 'Desalination' (0.28) due to the high weight given to 'Applicability &
423 demand' and the relatively low weight assigned to socio economy and costs by the stakeholders
424 who weighted the environmental dimension of sustainability highest.

425 For stakeholders weighing economy or society highest the most sustainable alternative was
426 alternative A2 'Compensating actions' (0.34; 0.33) followed by either A1 'Rain- & stormwater
427 harvesting' (0.22; 0.27) or A4 'Desalination' (0.23; 0.22). For the economy set of weights, A2
428 dominated the other three alternatives which obtained very similar total scores. For the society set
429 of weights A2 also dominated but the alternatives were more differentiated with the alternative A1
430 scoring higher than A4 which scored higher than A3. Here, the A4 Desalination alternative became
431 the second most sustainable alternative mainly due to high weight of 'freshwater withdrawal
432 impact', 'resilience' and 'political independency'.

433 For all 3 sets of weighting the alternative A3 'New well fields' had the lowest total scores (0.14;
434 0.21; 0.18) and was thereby the least sustainable option, regardless the applied stakeholder
435 perspective. In this way, the ASTA DSS emphasized that new well fields further away from the city
436 of Copenhagen is not the path to choose from a sustainability viewpoint.

437 **3.5.2 Evaluation of workshop**

438 The workshop was a convenient and structured way of scoring indicators of the society dimension
439 and assigning weights by using the 2 suggested multi-criteria decision aid methods, AHP and ROD.
440 Especially the ROD method was easily applicable as the stakeholders simply should rank the
441 sustainability dimensions and criteria by order and not assign a specific value or weight to each
442 criterion (or dimension). The participating stakeholders were very motivated, knowledgeable and
443 covered a broad range of viewpoints from NGO's over public administration and utilities to
444 knowledge institutions (Table 1). The main challenge was to reach agreements when conducting the
445 AHP and ROD analyses. Consensus was reached after some discussions, and therefore the results
446 appear relatively robust.

447 According to the ASTA DSS the assessment of the sustainability dimensions 'Environment' and
448 'Economy' does not involve stakeholder participation and it was therefore performed in advance
449 which allowed for the result of the ASTA DSS to be given immediately at the workshop. It
450 motivated the participants knowing the results would be presented at the end of the workshop.

451 'Environment' and 'Economy' were evaluated by specialist whereas 'Society' was evaluated at the
452 stakeholder workshop. Our experience with mixing the specialist and workshop evaluations,
453 confirmed this procedure to be both convenient and transparent method for combining multiple
454 criteria in a holistic assessment.

455 The workshop also gave the opportunity to exchange viewpoints on the technologies, and the
456 discussions among the stakeholders at the workshop showed a preference for groundwater
457 abstraction such as promoted by A2' Compensating actions'. Groundwater abstraction is a field of
458 well-established experience and knowledge among the stakeholders and they felt that development
459 and innovation should be focused on this field for our region.

460 3.5.3 Decision support aid

461 The result is now ready for use by decision makers who can determine which weighting set to select
462 for the final weighting for the decision support material – or which weights require further
463 development before they can be applied. Also the transparency of the cumulated results showing
464 contribution from individual criterion (Figure 5) provides help for the decision maker to document
465 why a certain alternative is the most sustainable alternative. As for Copenhagen's water supply
466 these results have supported implementation of compensating actions in combination with existing
467 groundwater abstraction. Our findings have also led to illustration of the positive effects of
468 softening water and central softening was introduced in summer 2017 for the first time in Denmark.
469 This underlines the importance of decision support aid and for the first time in our region a DSS, in
470 our case the developed ASTA DSS, is used to promote changes in the urban water system.

471 We selected a set of criteria and their coherent evaluation tool (e.g. environmental impacts – LCA)
472 which we together with the water utility considered relevant and essential to evaluate with the
473 purpose to identify the most sustainable alternative. This is in accordance with Xue *et al.* (2015)
474 who argue for the importance of developing decision support systems combining various criteria to
475 holistically evaluate the complete water system. Also Schoen *et al.* (2017) evaluated various criteria
476 (cost, energy, global warming, eutrophication and local human health) to identify the most
477 sustainable community water and sanitation service. In another study for Copenhagen Rygaard *et*
478 *al.* (2014) sets up similar criteria (cost, LCA impact categories, freshwater withdrawal impacts, risk
479 assessment, water self-sufficiency, demonstration value, resilience, etc) to evaluate the most
480 sustainable option. In comparison, the ASTA DSS integrates the assessments of the criteria in to
481 one sustainability score by applying weighting. This makes the decision making more transparent
482 and easier to convey the assessments.

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485 **4 Conclusion**

486 The development of the Decision Support System aimed at Assessing the most SusTainable
487 Alternative (ASTA DSS) and its application supported identification of the most sustainable future
488 supplementary water supply technology for Copenhagen. Based on this experience we conclude:

- 489 • The ASTA DSS generated a decision support incorporating three sustainability dimensions
490 (environment, economy and society) leaving the decision maker with transparent and well-
491 argued results making the decision easy to communicate. It also gave the decision maker the
492 possibility of changing weights e.g. by identifying three sets prioritizing either of the
493 sustainability categories highest to demonstrate the robustness of the decision.
- 494 • A stakeholder workshop was a convenient and structured way of involving all relevant
495 stakeholders in providing weights for the sustainability categories and the criteria of the
496 ASTA DSS and also for assessing the social indicators in a robust way, preparing for a
497 broader acceptance and robustness of the results and the decisions based on them.

498 Of four suggested alternatives for Copenhagen water supply we found that

- 499 • When the highest weight was assigned to the ‘Environment’ dimension of sustainability,
500 then the A1 alternative of ‘Rain- & stormwater harvesting’ was the most sustainable
501 followed by A4 ‘Desalination’.
- 502 When the highest weight was assigned to the ‘Economy’ or ‘Society’ dimension then the
503 most sustainable alternative was A2 ‘Compensating Actions’ followed by either A1 ‘Rain-
504 & stormwater harvesting’ or A4 ‘Desalination’.
- 505 • Regardless which sustainability dimension was given highest weight alternative A3 New
506 well fields came out with the lowest sustainability score.

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514

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Figure 1. The 4 alternatives and base case included in this study: A0 ‘Base alternative’ relying on groundwater abstraction; A1 ‘Rain- & stormwater harvesting’; A2 ‘Compensating actions’ consisting of water transfer in the affected catchment areas; A3 ‘Establishing new well fields’ 20 km further away from the waterworks; A4 ‘Desalination of seawater from Øresund’. The background is a map illustrating where the alternative is located in relation to the urban area (dark orange).

Figure 2. The decision hierarchy of how to assess the most sustainable alternative – the ASTA-model. The hierarchy contains three sustainability dimensions (environment, economy and society) and three levels (dimensions, criteria and indicators).

Figure 3. Saaty's 9 value scale (modified from Saaty, 2006) consisting of 5 verbal evaluations (1, 3, 5, 7 and 9) and their intermediates of importance or dominance when comparing one alternative over the other.

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651 **Figure 4.** Estimated investment, operation and maintenance cost of the four investigated
652 alternatives.

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Figure 5. The total scores from the multi-criteria assessment of the four alternatives combining the results for the 6 criteria: Total environmental impacts; Total toxicity impacts; Freshwater withdrawal impact; Costs; Customer values and Applicability & demand. The 3 sets of bars represent each of the stakeholder teams with the highest ranked Sustainability dimension being environment, economy or society respectively.

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List of Abbreviations

AHP	Analytical hierarchy process
ASTA	<u>A</u> ssess the most <u>s</u> ustainable <u>a</u> lternative
CBA	Cost-benefit analysis
DSS	Decision support system
EU-WFD	European Union’s Water Framework Directive
FWI	Freshwater withdrawal impact
LCA	Life-cycle assessment
MCDA	Multi-criteria decision analysis
ROD	Rank order distribution

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676 **Table 1.** List of participants of the Stakeholder Workshop.

Place of employment or representation	Number of participants
The Danish Nature Agency (the authority implementing the EU-WFD)	3
The Danish Competition and Consumer Authority	1
The Danish Water and Wastewater Association	1
The Danish Water Forum	2
The Geological Survey of Denmark and Greenland	2
The Technical University of Denmark, Department of Environmental Engineering	1
Consultancy in Environment and Construction	1
The Ecological Council, a Danish Non-governmental organization	1
Water customer	1
The water utility (HOFOR)	4
Total	17

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680 **Table 2**

681 Rank order distribution (ROD) weights (Roberts & Goodwin, 2002)

Number of Criteria									
Rank	2	3	4	5	6	7	8	9	10
1	0.6932	0.5232	0.4180	0.3471	0.2966	0.2590	0.2292	0.2058	0.1867
2	0.3068	0.3240	0.2986	0.2686	0.2410	0.2174	0.1977	0.1808	0.1667
3		0.1528	0.1912	0.1955	0.1884	0.1781	0.1672	0.1565	0.1466
4			0.0922	0.1269	0.1387	0.1406	0.1375	0.1332	0.1271
5				0.0619	0.0908	0.1038	0.1084	0.1095	0.1081
6					0.0445	0.0679	0.0805	0.0867	0.0893
7						0.0334	0.0531	0.0644	0.0709
8							0.0263	0.0425	0.0527
9								0.0211	0.0349
10									0.0173

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684 **Table 3.** Scores from the assessment of the 4 alternatives. Values were normalized against the total
685 score of the four alternatives to reflect the relative contribution to a total score of 1 at the criteria
686 and indicator level respectively. A high value was considered positive for the evaluation of the
687 alternative.

<i>Sustainability dimensions</i>	Criteria	Indicators	A1 Rain&stormwater	A2 Compensating actions	A3 New well fields	A4 Desali-nation
<i>Environment</i>	Environmental impacts**		0.369	0.253	0.227	0.151
		Global warming**	0.340	0.269	0.243	0.148
		Acidification**	0.474	0.198	0.177	0.151
		Nutrient enrichment**	0.425	0.223	0.200	0.152
	Toxicity impacts**		0.356	0.247	0.229	0.168
		Ecotoxicity water**	0.469	0.165	0.152	0.214
		Human toxicity soil**	0.303	0.307	0.274	0.116

	Human toxicity water**	0.294	0.200	0.202	0.304
Resource impacts	Freshwater withdrawal impact*	0.636	0.001	0.001	0.362
<i>Economy</i>	Socio economy				
	Benefits - costs*	0.052	0.480	0.286	0.182
<i>Society</i>	Customer values				
	Acceptance of & reliance on technology	0.059	0.557	0.291	0.093
	Aesthetics (perception & visual)	0.096	0.564	0.303	0.037
	Tourism & Contribution to Water Hub	0.375	0.375	0.125	0.125
	Applicability & Demand				
	Political independence	0.373	0.171	0.050	0.406

	Resilience	0.093	0.289	0.114	0.504
688	*Normalized reciprocals (1/x) were reported for quantified negative impacts. **For the LCA				
689	environmental and toxicity impacts, the score is based on the reciprocal of standardized distance to				
690	political target-values (Person equivalent targeted, PET) incorporated in the Life-cycle assessment				
691	(Wenzel et al., 1997).				
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704 **Table 4.** The AHP decision matrix of the indicator Acceptance & reliance on technology with
 705 relative importance/dominance values as found in the stakeholder workshop using the verbal score
 706 system (Figure 3.). Inconsistency ratio was 0.1 for this indicator.

	A1 Rain & stormwater r harvesting	A2 Compensatin g actions	A3 New well fields	A4 Desalination	Geometri c mean	Normalize d score
A1 Rain & stormwater harvesting	1	0.17	0.25	0.33	0.34	0.059
A2 Compensating actions	6	1	3	6	3.22	0.557
A3 New well fields	4	0.33	1	6	1.68	0.291
A4 Desalination	3.00	0.17	0.17	1	0.54	0.093

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711 **Table 5.** Rank ordering of sustainability categories and Criteria for the 3 stakeholder teams and
 712 determination of the associated three sets of weights by rank order distribution (ROD).

<i>Sustainability</i>	Set 1	Set 2	Set 3
<i>Category</i>	Most important:	Most important:	Most important:
Criteria	environment	economy	society
<i>Environment</i>	0.5232	0.3240	0.3240
Total environmental impacts	0.1528	0.32	0.3240
Total toxicity impacts	0.3240	0.1528	0.1528
Resource impacts	0.5232	0.5232	0.5232
<i>Economy</i>	0.1528	0.5232	0.1528
Socio economy	1.00	1.00	1.00
<i>Society</i>	0.3240	0.1528	0.5232
Customer values	0.3068	0.3068	0.6932
Applicability & demand	0.6932	0.6932	0.3068

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