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Integrated Assessment of Novel Urban Water Infrastructures in Frankfurt am Main and Hamburg, Germany

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Received: 24 November 2017; Accepted: 13 February 2018; Published: 16 February 2018

Abstract: Existing urban water infrastructures need to be modified if they are to cope with such challenges as demographic change, energy sufficiency and resource efficiency. It is believed that less centralised and hence more flexible systems adapt better to changing conditions. The main goal of this paper is to compare conventional and novel urban water infrastructures in five model areas in two German cities with regard to their sustainability. The novel technical options comprise modules such as blackwater and greywater separation, treatment and reuse as well as heat recovery, which are believed to be much more resource efficient than conventional systems. An assessment framework was developed which is able to comprehend corresponding transformation processes. An integrated assessment was conducted using multi-criteria decision analysis. The assessment results show that no particular technical option prevails over all the others and that the performance of the various options in the assessment is influenced by the general conditions found in the model areas. However, it can be concluded that novel water infrastructures can compete with or even perform better than conventional ones, especially when ecological and social criteria are emphasized.

Keywords: heat recovery; multi-criteria decision analysis; source separation; stakeholder participation; transformation; weighted sum model

1. Introduction

Existing infrastructures for urban wastewater disposal (and water supply) need to be transformed if they are to cope with such challenges as demographic and climate change, micropollutants, energy sufficiency or resource efficiency and conservation [1–3]. In this context, conventional centralised water infrastructures are less flexible in the face of changing conditions due to their long lifetimes, high capital investment and lengthy depreciation periods [4]. Because of these path dependencies, system transformations are neglected and only incremental improvements made [5,6]. Thus, centralised water infrastructures can be seen as a constraint for future transformations [6,7].

In contrast, it is believed that less centralised and hence more flexible systems adapt better to changing climatic and demographic conditions and use patterns [8–14]. Cities are thought to be highly vulnerable due to uncertain future developments and they should therefore change their water management and decrease their dependency on large-scale, energy-consuming water infrastructures [15]. Multiple and local water resources enable cities to reduce supply vulnerability by strengthening their resilience [16]. Furthermore, technological innovations, such as the separation of different domestic wastewater streams (e.g., greywater from showers and washing machines and blackwater from toilets), the use of treated wastewater for flushing toilets, watering and heat recovery, help reduce the ecological footprint [10,17–19]. However, such systems have so far only been implemented in individual cases in Germany mainly for financial reasons [14,19]. There are multiple technological components available for the abovementioned purposes that can be combined in various ways. Heat recovery from wastewater, for instance, can be carried out within a building, within a block of houses or at district level. The combination of these technical components produces a vast number of theoretically feasible technical options.

Furthermore, numerous semi-centralised designs (e.g., on the block or quarter level) are also possible in addition to decentralised and centralised infrastructures. Depending on the material flows considered, even hybrid forms of centralised and semi-centralised structures are conceivable, e.g., drinking water supply and blackwater disposal at the central level and greywater reuse and service water supply at a semi-central level. Such novel urban water infrastructures might play a crucial role in the transformation of conventional infrastructures but have not yet been implemented on a large scale or examined in detail.

Although the adoption of alternative water infrastructures, especially decentralised ones, is still rather rare [20,21], a number of examples can be found in the USA [22–25] and worldwide [26,27]. However, these cases are either examples of decentralised and centralised systems or examples of water reuse with a focus on indirect potable reuse or non-household uses (e.g., landscape irrigation, groundwater recharge, industrial use).

Hence, the main research question in this paper involved a comparison of conventional and novel water infrastructure systems in specific model areas in terms of their sustainability using an integrated assessment method. Therefore a corresponding assessment framework was applied which is able to comprehend innovation and transformation processes. Within this context, the assessment goal was to find the most sustainable option or the option with the greatest potential for transforming the existing infrastructure. A comprehensive and multi-dimensional understanding of sustainability was applied here [28–30]. Multi-criteria decision analysis (MCDA), a conventional method for resolving issues of this kind, was used in the study.

2. Materials and Methods

2.1. Case Studies and Technical Options

The assessment procedure and results to be presented in this paper are based on preceding research [16,31] which comprises, among others, the selection of five model areas as well as technological water infrastructure options. Three of the five model areas are located in the city of Frankfurt am Main, Germany, and two in the city of Hamburg, Germany. Frankfurt am Main, for instance, obtains its water resources from its hinterland where groundwater resources are already under pressure due to population growth and climate change [32].

All five model areas are currently the subject of an urban planning or conversion process, i.e., none of the proposed water infrastructures has been implemented here so far. The five model areas can be assigned to different land-use types: a commercial/industrial area, a conversion area and two development areas (well-located, built-up areas with partial fallow land) on the edge of the city centre, and one mixed-use area on the urban periphery [31]. All the selected neighbourhoods were on the verge of transformation, for instance from exclusively office or commercial areas to mixed use areas for commerce and living, as was the case in one of the neighbourhoods in Frankfurt am Main. Table 1 shows the characteristics of the model areas A to E (including sizes) and assigns them to land use types and spatial categories.

For each of these five model areas, three different technical water infrastructure options were ultimately assessed and compared. The options were all based on the following assumptions [31]: (i) The central water supply system basically remains unaffected, however some of the proposed technical options include the use of service water provided by treating greywater or rainwater (model area C). This will probably lead to a reduced consumption of potable water, which might necessitate a downsizing of pipeline schemes or even the construction of separate fire water supply pipelines. (ii) Rainwater is handled separately in the model areas, which is the requirement for focussing on domestic wastewater streams [33]. Conventional and novel water infrastructure options to some extent consider local infiltration of rainwater after appropriate treatment. Furthermore, green roofs are taken into account in some cases. (iii) Service water is only used for the purpose of flushing toilets (and not for showers, laundry and watering gardens, for example) in all the corresponding technical options owing to legal requirements.

The above-mentioned water infrastructure options of each model area consist of combinations of the following technical modules:

- conventional wastewater disposal and treatment
- greywater separation, treatment and reuse
- blackwater separation and treatment, possibly by using vacuum sewer systems for blackwater disposal
- heat recovery from wastewater (streams).

These modules can be compiled to general technical water infrastructure options which are described below [31]:

Conventional System Frankfurt: Wastewater in Frankfurt is collected and conveyed by a centralised combined and separate sewerage system. After treatment, the sewage sludge is incinerated without prior anaerobic digestion. Waste materials are used in the construction industry and heavy metals are deposited [34]. Electricity and heat from the combustion process are used. The conventional system reflects the current state of the art and can therefore be seen as a reference system.

Conventional System Hamburg: Wastewater disposal is carried out by a separate sewerage system. Sewage sludge and co-substrates are fermented and the fermentation residues and digester gas are incinerated [35]. The generated heat and electricity are used at the wastewater treatment plant. Additional heat is also used at an external container terminal [35]. Other than that, a small amount of purified biogas is fed as biomethane into the gas distribution system. Other incineration residues, i.e., ash and gypsum, are used as building materials in the construction industry and heavy metals are deposited [35]. Again, the conventional system serves as the reference system.

ConvGrey Frankfurt: In this water infrastructure option, light greywater (wastewater from showers, sinks and washing machines) and blackwater with heavy greywater (wastewater from toilets and kitchens) are collected and disposed separately (Figure 1). Blackwater with heavy greywater is treated conventionally while light greywater is treated separately and its heat is recovered. Any excess of light greywater is conveyed to the combined wastewater sewer; any excess of service water is either used externally (e.g., in other houses) or infiltrated (dashed lines in Figure 1). Treatment of light greywater and heat recovery takes place at house, block or quarter level, where a block comprises a block of houses and a quarter's area is identical to the model areas. At the block level, light greywater treatment is conducted by a fluid bed reactor including disinfection [36]. At the quarter level, full biological treatment including Phosphorus precipitation is used [37]. It is assumed that this technical option is generally used at the quarter level unless otherwise stated. Electricity and heat are generated from blackwater with heavy greywater at the central wastewater treatment plant, while energy and materials (i.e., heat for domestic hot water or heating, service water for toilet flushing) are obtained locally from light greywater. A technical option of this kind requires few behavioural changes from the users' point of view and is already being discussed by private investors and implemented locally at the house or block level. Various technical systems for this purpose are already available on the market. In addition, the legal and institutional framework is already relatively safe and has been proven to be manageable [36,38,39].

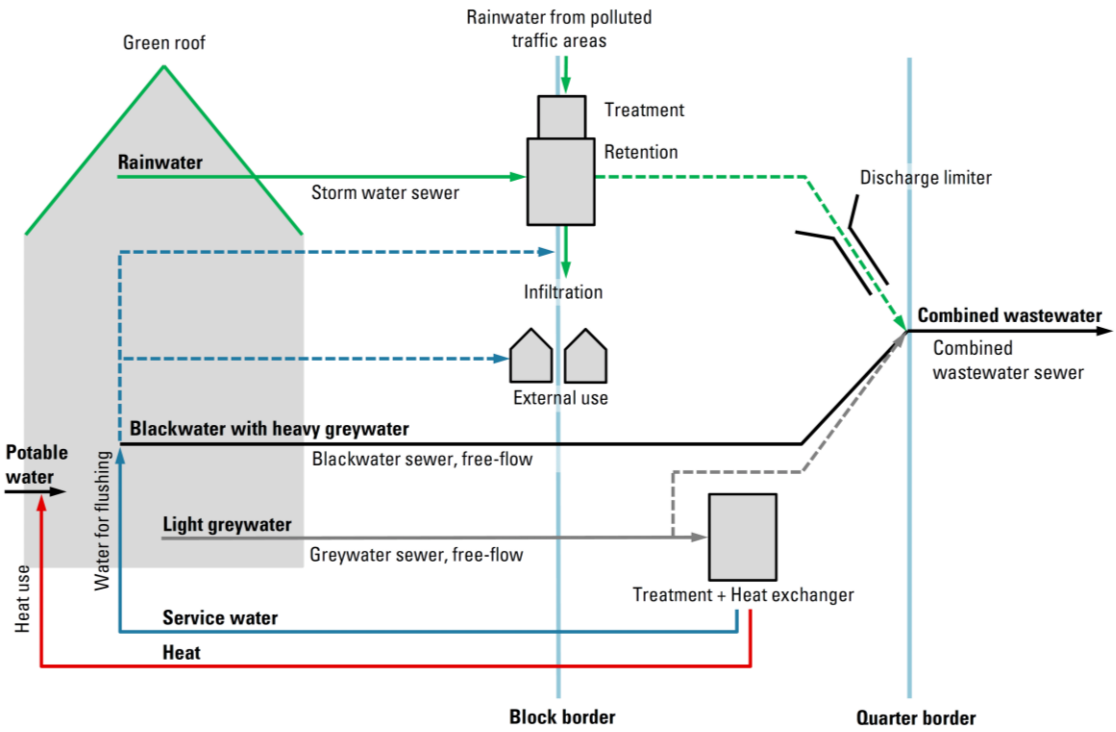

Figure 1. Scheme of the ConvGrey Frankfurt technical option at the quarter level (based on [31]).

ConvGrey Hamburg: In this technical option, greywater (light and heavy greywater, i.e., wastewater without toilet water) and blackwater (wastewater from toilets) are collected and conveyed separately (Figure 2). A vacuum sewer system can be used for blackwater at the quarter level. On the border of the quarter, it is conveyed to the conventional sewerage system. Greywater is treated for further use as service water and its heat recovered [37]. Any excess of greywater and service water (dashed lines in Figure 2) is handled just as in the case of ConvGrey Frankfurt. At the block level, greywater is treated with fluid bed reactors and then disinfected [36], while it is assumed that full biological treatment including P precipitation is used for this purpose at the quarter level [37], unless otherwise stated. The idea behind this technical option is to link areas with the same infrastructure and convert them into the Hamburg Water Cycle (HWC, see below) technical option. In contrast to the ConvGrey Frankfurt option, greywater rather than light greywater is collected and treated. The vacuum sewer system requires less water to convey blackwater and hence requires less water for flushing toilets.

Hamburg Water Cycle (HWC): Blackwater and greywater are collected and disposed separately in the HWC (Figure 3; [40]). Greywater is treated biologically including P precipitation so that it can be used for infiltration (dashed lines in Figure 3). Blackwater is conveyed by a vacuum sewer system and treated with co-substrates (organic waste) and sewage sludge from the greywater treatment process through a continuously stirred tank reactor (CSTR) and an upflow anaerobic sludge blanket (UASB). Solid and liquid components are separated. The liquid phase is treated in the UASB, the solid phase in the CSTR. Recovered biogas is used for power generation. The solids of the digestate can be used for composting, the production of compost or agricultural purposes. The liquid phase of the digestate is conveyed to the greywater treatment and used with the treated greywater as service water [37]. Any excess of service water is either used externally or infiltrated (dashed lines in Figure 3). The proposed technical option is an alternative version of the original HWC [37], which has not yet been implemented. It requires less treatment and provides a better reuse of resources from the (highly concentrated) blackwater, better treatability of pharmaceutical residues and pathogens, relief for sewers and increased biogas production. This makes the quarter self-sufficient in terms of energy and improves its carbon footprint.

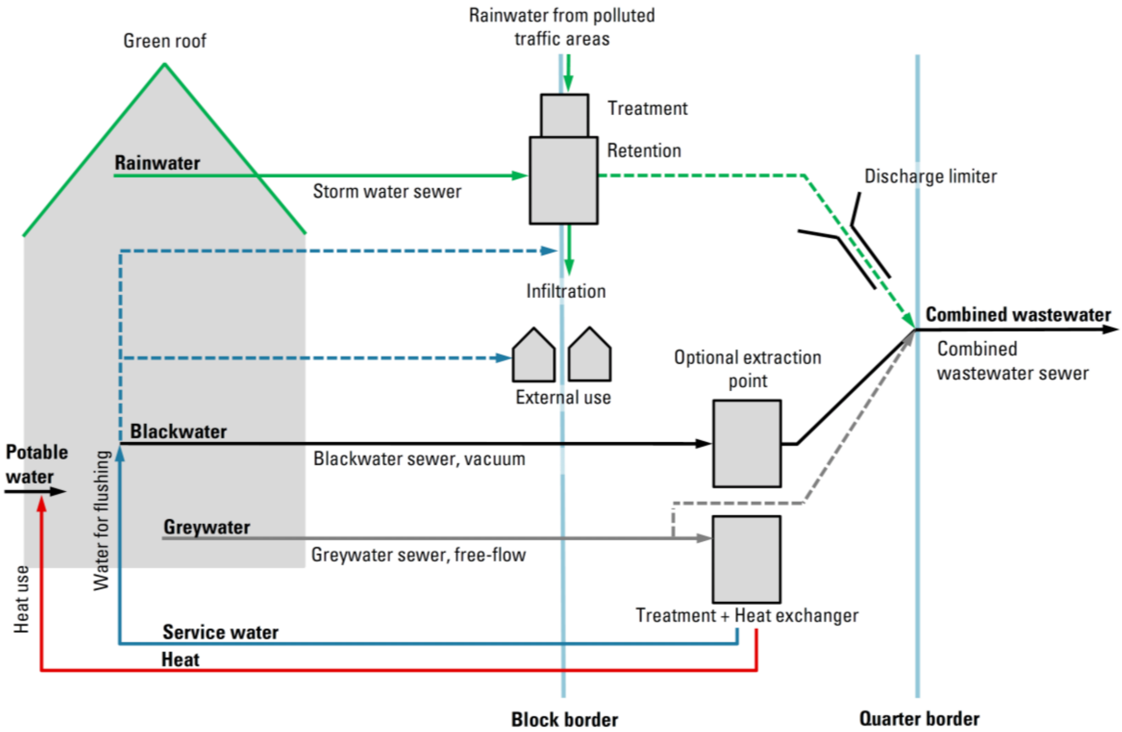

Figure 2. Scheme of the ConvGrey Hamburg technical option at the quarter level (based on [31]).

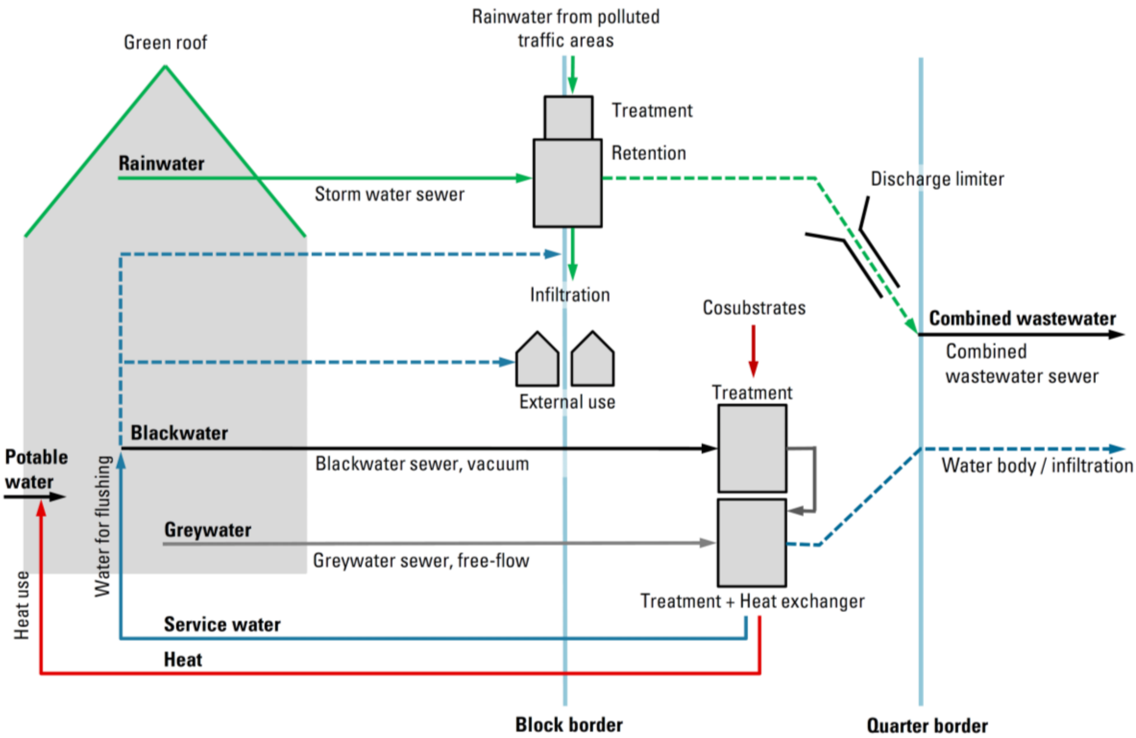

Figure 3. Scheme of the Hamburg Water Cycle (with heat recovery) technical option at the quarter level (based on [31]).

The general technical options presented have slight modifications in order to consider local conditions and requirements of the five model areas. The assessment process is finally based on three specific options for each model area: one conventional water infrastructure option (reference option) and two novel water infrastructure options (Table 1).

Table 1. Technical water infrastructure options for model areas (based on [31]).

Model Area	Land Use Types, Spatial Categories and Sizes	Reference Option	Novel Option 1	Novel Option 2
		Frankfurt am Main		
A	Conversion area, edge of city centre, 15.75 ha	Conventional system Frankfurt	ConvGrey Frankfurt (quarter level)	Hamburg Water Cycle with heat recovery
B	Mixed use area, urban periphery, 63.34 ha	Conventional system Frankfurt	ConvGrey Frankfurt (block level)	ConvGrey Frankfurt (quarter level)
C	Commercial/industrial area, edge of city centre, 28.5 ha	Conventional system Frankfurt	ConvGrey Frankfurt without greywater treatment, only heat recovery from greywater at block level; additional heat recovery from combined wastewater	Conventional system Frankfurt with heat recovery and service water use from rainwater
		Hamburg		
D	Development area, edge of city centre, 5.2 ha	Conventional system Hamburg	Conventional system Hamburg with heat recovery	ConvGrey Hamburg (quarter level)
E	Development area, edge of city centre, 13.5 ha	Conventional system Hamburg	ConvGrey Hamburg (quarter level) with additional heat recovery from combined wastewater	ConvGrey Hamburg (block level)

2.2. *Methodology*

2.2.1. Stakeholder Involvement

A participatory approach allowed relevant actors in the planning and decision-making around the novel water infrastructures to participate in the assessment process. This was accomplished by holding preliminary roundtable discussions and, most importantly, three participatory stakeholder workshops. In order to prepare for the workshops with relevant stakeholders, roundtable discussions with scientists, representatives of professional (technical) associations and technical authorities were conducted. The discussions with other scientists from research projects dealing with the assessment of novel water infrastructure systems covered the assessment framework and the methodological questions. Specifying the assessment framework mainly aimed at defining the system boundaries and the assessment goal(s). Representatives from water supply, wastewater disposal, energy and district heating associations and organisations then took part in the discussions with professional associations and authorities. Issues with regard to the contents, current problems and future prospects of conventional and novel water infrastructures were discussed.

Three stakeholder workshops were conducted in total. The first workshop aimed at identifying relevant assessment categories and criteria with stakeholders from the authorities, especially urban planning, interest groups, involved companies, utilities and science. This workshop took place a few months after the beginning of the assessment process and stakeholders from both model cities were invited to establish a common basis for the assessment process. In total, 20 participants attended the workshop. The researchers subsequently created a structure for the criteria that had been identified. In order to avoid "blind spots", existing sets of assessment criteria [41] and indicators from technical guidelines of the German water sector [33] were used to fill any gaps where necessary. Apart from this, the abovementioned multi-dimensional sustainability concepts [28–30] helped to scrutinise the completeness of the set of criteria.

Based on the compiled list of assessment criteria, data integration and the assessment process itself were conducted by an interdisciplinary team of researchers and industry partners of the overarching research project of which the presented assessment process is only a part. The data consisted of qualitative statements, available quantitative data, results of material flow analyses [31] and cost estimates of the specific technical options for example (Supplementary Table S1). Finally, the aim of the second and third workshops, which took place about one year after the first workshop, was to present and discuss preliminary assessment results and, most importantly, weight the assessment categories and criteria with regard to their importance or relevance from the stakeholders' points of view. One workshop was held in Frankfurt (with 15 participants) focusing exclusively on the model areas in Frankfurt and another was held in Hamburg (with 12 participants).

2.2.2. Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) is suitable for comparing specified options with regard to the identified assessment criteria and can therefore be applied here. In doing so, the specific technical option with the highest utility value in terms of the aforementioned assessment goal can be identified in each model area. Such methods for assessing options are obviously much more comprehensive than conventional monetary and/or one-dimensional tools for decision analysis, such as cost-benefit analysis [42]. MCDA tools are able to consider an arbitrary number of assessment criteria, which can be monetary and non-monetary as well as quantitative and qualitative. This means that one-sided decisions driven purely by economic aspects can be avoided, allowing other aspects such as ecological and social benefits to be included in the assessment. In addition, the integrated assessment presented here was a holistic approach that corresponded far more to an integrated mode of research capable of tackling complex systemic challenges such as those mentioned above [43]. Apart from that, MCDA methods have been applied in the water sector already and have proven to be successful [44–55].

The MCDA methods taken into consideration for the sustainability assessment were the Weighted Sum Model (also known as Utility Analysis) [56–58], the Analytical Hierarchy Process (AHP) [59,60] and the Analytical Network Process (ANP) [61]. The Weighted Sum Model was eventually chosen over the other methods due to its greater transparency and traceability. Both aspects were given greater importance within a participatory approach than would be the case in a purely scientific study without any societal relevance. Nevertheless, the weaknesses and pitfalls of the method [62] were also taken into account in the subsequent process (e.g., preferential independency, double counting).

Within the Weighted Sum Model, the (total) utility value of an option can be calculated as follows:

$$U_i = \sum_{j=1}^{n} w_j u_{ij}$$

for $i = 1, 2, 3, \ldots\ m$
U_i = total utility value of an option i
u_{ij} = achievement degree of an option i regarding a criterion j
w_j = weight of a criterion j

Qualitative data have to be transformed into quantitative values using a transformation function. In our case, qualitative assessments using a high–medium–low scale, for instance, were transformed by a linear function into achievement degrees of two, one and zero respectively. Quantitative data can also be converted into achievement degrees of two, one and zero by assigning them to the maximum, medium and minimum value measured. After each option's utility value has been determined, they can be compared to one another on an ordinal scale. The procedure results in a ranking of the options according to the defined assessment goal. The option with the highest utility value is the most sustainable water infrastructure system in a given model area compared to the other options.

2.2.3. Criteria Weighting

Several "weighting scenarios" were applied to the assessment results (Table 2). Three weighting scenarios were determined in advance by the team of researchers in order to represent a broad range of contrasting weightings. An additional weighting scenario was compiled by the stakeholders in each model city to integrate their preferences. In the first weighting scenario, all four eventually selected categories (i.e., technology, ecology, economy, society) had an equal weight of 25%. The indicators' weights came from the number of indicators in a category (category weight divided by number of indicators) and were equally distributed within a category. In the second weighting scenario ("Tech+Econ"), the technological and economic category had a weight of 41.7% each and the ecological and social category 8.3% each. This weighting scenario represented a conventional assessment approach focussing on economic and technical aspects. The actual weights resulted from a cross-impact analysis among the four categories in which a category received two points if it was rated higher than another category and one point if two categories were equivalent. In this way, the technical and economic category each gained five points in total (out of 12 points distributed to all four categories) and the ecological and social one point each. In the third weighting scenario ("Ecol+Soc"), the ecological and social category correspondingly had a weight of 41.7% each and the technological and economic category 8.3% each. This "scenario" represented a contemporary or alternative assessment approach placing more weight on ecological and social aspects.

The stakeholders' weightings were discussed and determined by all of the actors involved for each city separately. In terms of the categories, this was achieved through negotiations between the stakeholders. In terms of the criteria/indicators, the stakeholders were asked to award points, which is why their weights were not equally distributed, in contrast to the other weighting scenarios. The number of points was then converted into percentages for each indicator (Table 2). Other than that, the weighting scenarios were used to test and verify the assessment results and therefore practically served as a sensitivity analysis.

Table 2. List of assessment criteria and indicators for the impact assessment and weighting scenarios.

Category/Field of Action	**Criterion**	**Indicator**	**Weighting scenario/Weight [%]**				
			Equally Weighted	**Tech+Econ**	**Ecol+Soc**	**Stakeholders Frankfurt**	**Stakeholders Hamburg**
Technology			25.0	41.7	8.3	25.0	30.0
Integrability	Impact on existing infrastructure and buildings	Need for adaptation of existing water/building infrastructure [low, medium, high]	5.0	8.3	1.7	5.0	5.3
	Synergetic potential	Synergies with other infrastructures and concerning renewable energy (waste heat, cooling buildings, biogas etc.) [high, medium, low]	5.0	8.3	1.7	3.8	7.5
Adaptability	Flexibility	Degree of flexibility regarding changes in climate, demography, law, usage patterns etc. [high, medium, low]	5.0	8.3	1.7	6.9	5.3
Operational reliability/robustness	Process stability	Impact of extreme events (heavy rainfall, wastewater reduction, power failure, vandalism etc.) [low, medium, high]	5.0	8.3	1.7	5.0	5.3
		Effects of failure of individual system components (resilience) [low, medium, high]	5.0	8.3	1.7	4.4	6.8
Ecology			25.0	8.3	41.7	27.5	23.8
Resource protection	Local ecosystem functions	Contribution to the production, preservation and strengthening of blue and green infrastructure [high, medium, low]	3.6	1.2	6.0	3.4	3.4
	Water protection (surface waters)	Reduction of inputs of nutrients (N, P) and ecotoxicological substances [high, medium, low]	3.6	1.2	6.0	4.9	2.1
	Soil and groundwater protection	Reduction of inputs of ecotoxicological substances [high, medium, low]	3.6	1.2	6.0	5.4	2.5
	Energy and climate protection	Emission of greenhouse gases (CO_2 equivalents) [t/a]	3.6	1.2	6.0	5.9	3.8
Resource use	Resource balance	Drinking water demand [m^3/a]	3.6	1.2	6.0	2.5	2.5
		Electricity demand [MWh/a]	3.6	1.2	6.0	2.9	4.2
		Heat recovery [MWh/a]	3.6	1.2	6.0	2.5	5.1

Table 2. *Cont.*

Category/Field of Action	Criterion	Indicator	Weighting scenario/Weight [%]				
			Equally Weighted	Tech+Econ	Ecol+Soc	Stakeholders Frankfurt	Stakeholders Hamburg
Economy			25.0	41.7	8.3	25.0	21.3
Utilities, investors	Costs	Annual costs [€/a]	5.0	8.3	1.7	6.3	4.3
	Revenues	Potential revenues from products of novel water infrastructure systems [€/a]	5.0	8.3	1.7	2.5	2.7
	Long-term competitiveness, innovation leadership	Effects on image and know-how [high, medium, low]	5.0	8.3	1.7	4,4	5.8
	Ability of system change (flexibility)	Duration of depreciation [low, medium, high]	5.0	8.3	1.7	3.8	3.7
Investors, residents	Economic viability	Impact on specific costs (rent, rent including heating) [low, medium, high]	5.0	8.3	1.7	8.1	4.8
Society			25.0	8.3	41.7	22.5	25.0
Exclusion	Socio-economic, cultural barriers	Risk of exclusion [low, medium, high]	8.3	2.8	13.9	7.5	3.1
Usability, practicality	Ease of handling	Ease of use for operators and residents [high, medium, low]	8.3	2.8	13.9	8.4	15.6
Environmental awareness	Awareness raising regarding resource use (water, energy)	Sensitisation potential (residents, operator, investor, politics) [high, medium, low]	8.3	2.8	13.9	6.6	6.3

2.2.4. System Boundaries and Assessment Goals

The preliminary roundtable discussions resulted in three assessment levels or scopes that differed in terms of their system boundaries (Table 3), however the main focus in this paper was on assessment level one: the short-term view of the model areas. The research question was: Which specific technical option is the most sustainable in each model area compared to the other options? This question referred to concrete project planning in the five model areas and therefore covered a period of up to approximately ten years.

Table 3. Assessment framework [63].

Assessment Level	**1**	**2**	**3**
Spatial scope	Model areas	Model cities	Types of regions
Temporal scope	Short-term	Medium-term	Long-term
Research question	Which specific technical option is the most sustainable in each model area compared to the other options?	Which of the novel general technical options has the greatest transformation potential at city level?	Which of the technical modules has the greatest transformation potential in different types of regions?
Addressees	Investors/builders, planners, supply and disposal utilities	Policy-makers, city councils, supply and disposal utilities	Policy-makers, technical authorities, technical and municipal associations, business companies, science

Assessment level two was based on the results of the comparative assessment undertaken at assessment level one and widened the focus to the entirety of the model cities (in this case Frankfurt and Hamburg). The research question was: Which of the new general technical options (i.e., the two ConvGrey options) has the greatest transformation potential at city level? If it is assumed that one of the new general technical options will be implemented across the city with high development dynamics and low transformation efforts, which of the options has the greatest potential? Since this scenario encompassed a large-scale transformation of the model cities, a period of a couple of decades could be assumed here.

Finally, assessment level three tried to answer the question: Which of the technical modules (e.g., greywater separation and reuse plus heat recovery) has the greatest transformation potential in different types of regions? These types of regions comprise growing and shrinking urban agglomerations as well as rural areas. Since these kinds of transformations take a very long time, a period of up to 100 years or even longer was considered here.

All three assessment levels attempted to answer the question of whether and under what conditions conventional or novel water infrastructures are more sustainable or have greater transformation potential. Apart from this, the assessment scopes were addressed to stakeholders at different political or organisational levels and in different sectors (Table 3). The local scope of assessment level one, for instance, included investors and urban planners as well as supply and disposal utilities, whereas assessment level two was also addressed to (urban) policy makers and city councils. Assessment level three referred to nationwide technical and municipal associations, businesses and, last but not least, scientists.

3. Results and Discussion

3.1. Assessment Categories and Criteria

As a first step, the stakeholder process produced a set of indicators comprising 31 items and covering a total number of seven categories representing a broad range of topics such as technological, ecological, economic, social, organisational and legal aspects, as well as governance. Internal discussions among the researchers resulted in the differentiation of criteria and indicators describing the direct impacts of the technical options (e.g., impact on existing infrastructure and buildings) whereas others represented the requirements of a transformation process (e.g., adaptation of organisational structures).

Categories describing the requirements of a transformation process were “organisation”, “legal aspects” and “governance”. Many of the eleven criteria within these categories represented adaptation needs and efforts, for instance laws, technical guidelines or urban development contracts, but also organisational structures within the wastewater utility that have to be adapted in order to implement novel water infrastructure systems. In the conventional systems (reference option), the efforts or requirements were generally lower since the infrastructure system was “only” being optimised and there were no systemic changes involved (in contrast to the novel systems).

In this paper, criteria and indicators describing the impacts of the various options were considered in the actual assessment. Table 3 shows the final set of categories, criteria and indicators, their dimensions and their weightings within different weighting scenarios. The list comprises the four (impact) categories “technology”, “ecology”, “economy” and “society” including 20 indicators identified jointly by the stakeholders and researchers. Hence, it also represents the multi-dimensional sustainability concepts considered.

3.2. Assessment Results

The assessment process was carried out based on the developed set of criteria and resulted in utility values and rankings of three compared water infrastructure options in each of the five model areas (Table 4). Based on the stakeholders’ criteria and weightings, the options were assessed by project researchers responsible for a specific topic or category because they were also undertaking relevant research and hence had the largest database and/or overview of their topics. This approach enabled the technical option with the highest utility value of each of the five model areas to be determined within each weighting scenario. (The achievement degrees of all options and all indicators can be found in Supplementary Table S1.)

Table 4. Assessment results of water infrastructure options in the model areas (first ranks are highlighted).

Model Area/Weighting Scenario	Reference Option		Novel Option 1		Novel Option 2	
	Utility Value	**Rank**	**Utility Value**	**Rank**	**Utility Value**	**Rank**
Frankfurt am Main						
A	Conventional system Frankfurt		ConvGrey Frankfurt		HWC with HR	
Equally weighted	89	1	84	2	76	3
Tech+Econ	83	1	68	2	59	3
Ecol+Soc	95	2	99	1	93	3
Stakeholders	99	1	86	2	73	3
B	Conventional system Frankfurt		ConvGrey Frankfurt (block level)		ConvGrey Frankfurt (quarter level)	
Equally weighted	80	2	87	1	78	3
Tech+Econ	80	1	69	2	66	3
Ecol+Soc	81	3	105	1	90	2
Stakeholders	89	1	82	2	75	3
C	Conventional system Frankfurt		ConvGrey Frankfurt (1)		Conventional system Frankfurt with HR (2)	
Equally weighted	90	2	98	1	78	3
Tech+Econ	83	1	79	2	73	3
Ecol+Soc	96	2	117	1	84	3
Stakeholders	97	1	90	2	75	3
Hamburg						
D	Conventional system Hamburg		Conventional system Hamburg with HR (4)		ConvGrey Hamburg(quarter level)	

Table 4. *Cont.*

Model Area/Weighting Scenario	Reference Option		Novel Option 1		Novel Option 2	
	Utility Value	**Rank**	**Utility Value**	**Rank**	**Utility Value**	**Rank**
Equally weighted	97	2	110	1	78	3
Tech+Econ	86	2	97	1	66	3
Ecol+Soc	108	2	124	1	91	3
Stakeholders	99	2	106	1	71	3
E	Conventional system Hamburg		ConvGrey Hamburg (quarter level) (3)		ConvGrey Hamburg (block level)	
Equally weighted	90	1	82	2	82	2
Tech+Econ	83	1	74	2	74	2
Ecol+Soc	96	1	89	2	89	2
Stakeholders	92	1	72	3	74	2

Tech = technology; Econ = economy; Ecol = ecology; Soc = society; HR = heat recovery; HWC = Hamburg Water Cycle. (1) without greywater treatment, only heat recovery from greywater at block level; with additional heat recovery from combined wastewater; (2) with service water use from rainwater; (3) with additional heat recovery from combined wastewater; (4) It should be noted that this technological option is a conventional system that has been equipped with heat recovery, while energy aspects were not considered in the corresponding reference option. The option therefore gains an advantage but does not transform the existing water infrastructure.

The results showed that out of 20 possible first rankings, conventional options were given the highest utility value eleven times, while novel or at least adapted conventional systems had the highest utility value nine times. Five of the latter systems were "ConvGrey" systems with greywater separation (with or without greywater treatment) and four were (adapted) conventional water infrastructure systems equipped with heat recovery (as in the case of model area D).

While the results in Frankfurt's model areas were rather varied, i.e., conventional and novel options scored equally well depending on the weighting scenario (e.g., model area B, Figure 4), the results in Hamburg were clearly dominated by one technical option in each model area. In Hamburg's model area D, the conventional option equipped with heat recovery ranked highest in all weighting scenarios. In model area E, the novel water infrastructure options could not compete with the conventional system, possibly due to the fact that both corresponding novel options have technically already been prepared for conversion into HWC systems in the future. This means that they carry the burden of higher costs due to their technical complexity (e.g., vacuum sewers) but have possibly not yet been rewarded for their potential benefits. However, Frankfurt's model area A proved that its HWC option including heat recovery was evidently inferior compared to the conventional system and the ConvGrey option (Table 4). Nevertheless, general conclusions could not be drawn from the latter example since the results were case specific and every model area had its own conditions and requirements.

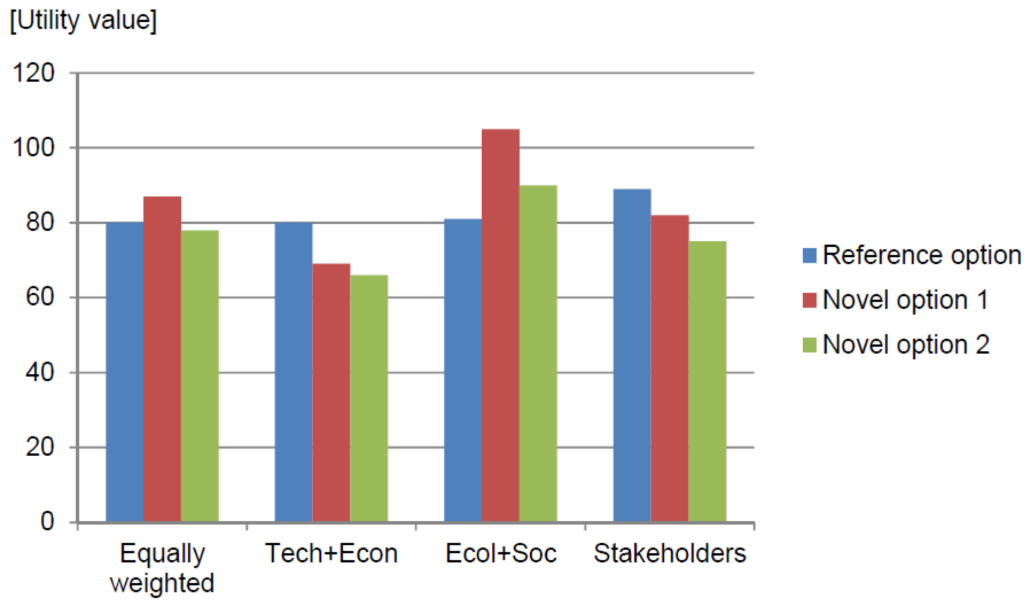

Figure 4. Utility values of water infrastructure options in model area B depending on weighting scenario ("Tech+Econ" = weighting scenario with emphasis on technological and economic category; "Ecol+Soc" = weighting scenario with emphasis on ecological and social category; "Stakeholders" = weighting scenario with the stakeholders' weightings).

When taking a closer look at the weighting scenarios, it could be seen that with equal weightings novel options had the highest utility value in three cases (model areas B, C, and D) while conventional systems were at the top in two model areas (A and E). The weighting scenario with an emphasis on the technical and economic assessment category resulted in four highest rankings for the conventional options, except in one case (model area D). This was mainly due to the fact that these systems generally perform well regarding the categories technology and economy (e.g., model area A, Figure 5). However, it should be emphasised that novel water infrastructure options have consistently prevailed over conventional options within the technological category in terms of flexibility and adaptability, as well as their synergy potential with other infrastructures and within the economic category in terms of revenue, long-term competitiveness or innovation leadership and the ability of system change (Supplementary Table S1). The higher valuation of conventional options was mainly due to the fact that they were considered to have a lower need for adaptation concerning existing infrastructures.

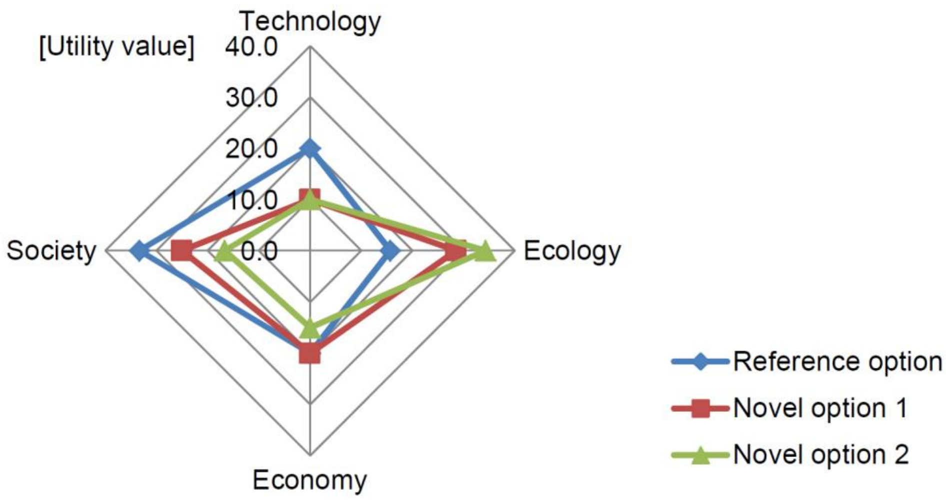

Figure 5. Utility values of water infrastructure options in model area A depending on category (equally weighted).

Novel water infrastructures, in contrast, have the highest utility value in four model areas if social and ecological categories and criteria are weighted higher due to their good performance in the corresponding categories (e.g., model area C, Figure 6). The only exception was model area E, for the abovementioned reasons.

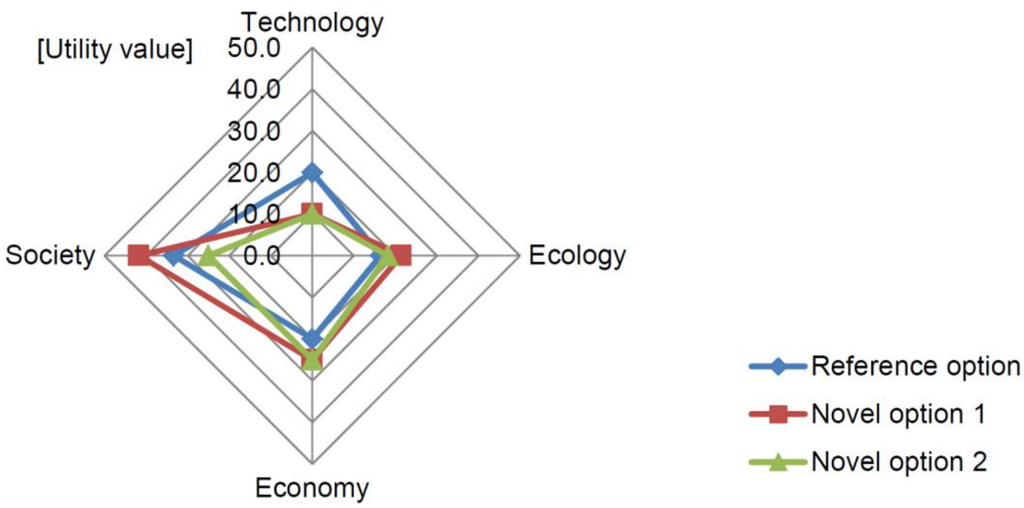

Figure 6. Utility values of water infrastructure options in model area C depending on category (equally weighted).

Interestingly, the stakeholders' weightings always had the same outcome as the technological and economic weighting scenario. Although stakeholders particularly valued the ecological benefits of the novel systems, monetary and technical arguments still seemed to be important to them. Finally, a conventional option ranked third in just one case (model area B) in an ecological and social weighting scenario. Apart from this, only novel water infrastructure options came last.

Finally, a manual sensitivity analysis was carried to reveal the criteria which contributed in particular to the performance of a technical option in the assessment. The reference option always performed best in terms of its low impact on existing infrastructure (i.e., need for adaptation of existing water/building infrastructure), its low annual costs and good economic viability (impact on specific costs, e.g., rent, rent including heating), its good usability and practicality (e.g., ease of handling, ease of use for operators and residents) as well as its few socio-economic and cultural barriers (e.g., risk of exclusion). The novel water infrastructures partially scored well in terms of their synergetic potential with other infrastructures (e.g., waste heat, cooling buildings, biogas), their systemic flexibility (e.g., regarding changes in climate, demography, law, usage patterns), their good resource balance (in particular heat recovery if this technology was involved), potential revenues from products and their awareness raising regarding resource use.

4. Conclusions

The question as to whether conventional or novel urban water infrastructures are more sustainable can be answered depending on how much emphasis is placed on technological and economic or ecological and social criteria. This should not be misinterpreted as being bad news for novel options, but rather should lead to a reassessment of the general assumptions made about conventional water infrastructures. Novel water infrastructures can not only compete with conventional ones but even perform better than these, especially when ecological and social criteria are emphasized, but also in terms of certain technological and economic criteria, such as adaptability, flexibility, synergy potential, revenues and innovation leadership.

It is assumed that water infrastructures will continue to be characterized by an increasing diversification of conventional and novel systems. An integrated assessment provides a good basis for the identification of the novel infrastructure option with the greatest transformation potential. In doing so, the options' impacts, transformation efforts, and arising opportunities have to be assessed. Even though no specific novel option has prevailed over the other alternatives, the assessment results suggest that the novel systems examined here will play a crucial role in the transformation of the existing water infrastructure.

Nevertheless, it should be stressed that the most sustainable technical option in a specific model area is not necessarily also the one with the highest transformation potential for an urban district, a growing agglomeration or a structurally weak area. A model area's infrastructure has numerous impacts on and interfaces with the city-wide infrastructure. These can be grasped as external effects and are essential at assessment level two (city level), for instance. An advancing implementation of novel water infrastructures leads to potential changes in the municipal water infrastructure (e.g., under-utilization) that should be viewed from the long-term perspective of a system transformation of the whole city. Therefore, a wider spatial and temporal scope has to be considered in order to minimize possible negative repercussions and to enhance corresponding synergies and potentials.

A major novelty of the assessment framework developed in this study is that it is able to take aspects of innovation and transformation into account. Innovation and transformation, however, are of course not confined to technological issues but, for instance, also refer to social and ecological issues. Thus, the advantages and disadvantages of innovative and conventional options alike can be incorporated comprehensively. In terms of the assessment process, it is an important finding that surrounding conditions and requirements of the transformation process have to be handled separately from the direct impacts of a transformation due to the fact that novel options often go hand in hand with systemic changes compared to "only" optimised conventional options. However, how these transformation efforts for surrounding conditions are concretely handled in an assessment process remains an open question for further research.

Supplementary Materials: The following is available online at www.mdpi.com/2073-4441/10/2/211/s1, Table S1: Methods of data collection regarding assessment criteria and indicators as well as achievement degrees of compared options.

Acknowledgments: The authors would like to thank all partners in the netWORKS 3 project, in particular Martina Winker, and HAMBURG WASSER for their collaboration and support, as well as the project stakeholders who have contributed to this work through fruitful discussions and comments. This work was accomplished within the project "netWORKS 3: Intelligent integrated water management solutions in Frankfurt am Main and Hamburg" (grant number 033W006A), which is funded by the German Federal Ministry of Education and Research (BMBF).

Author Contributions: Martin Zimmermann, Jörg Felmeden and Bernhard Michel developed the concept, gathered the data and discussed the results. Martin Zimmermann wrote the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hüttl, R.; Bens, O. (Eds.) *Georessource Wasser—Herausforderung Globaler Wandel. Beiträge zu Einer Integrierten Wasserressourcenbewirtschaftung in Deutschland (Water as a Geological Resource—Challenge Global Change. Contributions to an Integrated Water Management in Germany)*; Deutsche Akademie der Technikwissenschaften (acatech): Munich, Germany, 2012.
2. Hillenbrand, T.; Hiessl, H.; Klug, S.; von Lüninck, B.; Niederste-Hollenberg, J.; Sartorius, C.; Walz, R. *Herausforderungen Einer Nachhaltigen Wasserwirtschaft*; Innovationsreport (Challenges of a Sustainable Water Management. Innovation Report); Arbeitsbericht 158; Büro für Technikfolgenabschätzung Beim Deutschen Bundestag (TAB): Berlin, Germany, 2013; Available online: https://www.tab-beim-bundestag.de/de/pdf/publikationen/berichte/TAB-Arbeitsbericht-ab158.pdf (accessed on 20 January 2016).
3. Schramm, E.; Kluge, T.; Beck, S.; Hansjürgens, B.; Hiessl, H.; Sartorius, C. Integrierte Systemlösungen als Strategie für eine nachhaltige und exportstarke Wasserwirtschaft (Integrated system solutions as strategy for a sustainable water management with export strength). *Wasser Abfall* **2013**, *15*, 39–44. [CrossRef]
4. Hillenbrand, T.; Hiessl, H. Sich ändernde Planungsgrundlagen für Wasserinfrastruktursysteme. Teil 1: Klimawandel, demographischer Wandel, neue ökologische Anforderungen (Changing planning basis for water infrastructure systems. Part 1: Climate change, demographic change, new ecological requirements). *KA Wasserwirtsch. Abwasser Abfall* **2006**, *53*, 1265–1271.
5. Nowak, M.; Guenther, E. Scenario planning: Managing the effects of demographic change on East German wastewater companies. In *H2O—Wasser*; Ökonomie und Management Einer Schlüsselressource: Berlin, Germany, 2010; pp. 45–63.
6. Schramm, E.; Kerber, H.; Trapp, J.H.; Zimmermann, M.; Winker, M. Novel urban water systems in Germany: Governance structures under transformation. *Urban Water J.* **2017**, *6*, 1–10. [CrossRef]
7. Moss, T. 'Cold spots' of Urban Infrastructure: 'Shrinking' Processes in Eastern Germany and the Modern Infrastructural Ideal. *Int. J. Urban Reg. Res.* **2008**, *32*, 436–451. [CrossRef]
8. Wikramanayake, N.; Corea, E.J.H. Alternative Technology for Urban Wastewater Treatment: Case Studies and Issues of Implementation and Sustainability. In Proceedings of the World Water and Environmental Resources Congress, Philadelphia, PA, USA, 23–26 June 2003; Bizier, P., DeBarry, P., Eds.; American Society of Civil Engineers: Reston, VA, USA, 2003.
9. Daigger, G. Wastewater management in the 21st century. *J. Environ. Eng.* **2007**, *11*, 671–680. [CrossRef]
10. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (DWA). *Neuartige Sanitärsysteme (NASS) (Novel Sanitary Systems (NASS))*; German Association for Water, Wastewater and Waste (DWA): Hennef, Germany, 2008.
11. Tukker, A.; Charter, M.; Vezzoli, C.; Stø, E.; Munch Andersen, M. (Eds.) *System Innovation for Sustainability 1: Perspectives on Radical Change to Sustainable Consumption and Production*; Greenleaf Publishing: Sheffield, UK, 2008.
12. Bieker, S. *Semizentrale Ver- und Entsorgungssysteme: Neue Lösungen für Schnell Wachsende Urbane Räume. Untersuchung Empfehlenswerter Größenordnungen (Semicentral Supply and Disposal Systems—New Solutions for Fast Growing Urban Areas. Investigations of Recommended Scales)*; Institute IWAR: Darmstadt, Germany, 2009.
13. Felmeden, J.; Kluge, T.; Koziol, M.; Libbe, J.; Michel, B.; Scheele, U. *Öko-Effizienz Kommunaler Wasser-Infrastrukturen. Bilanzierung und Bewertung Bestehender und Alternativer Systeme (Eco-Efficiency of Municipal Water Infrastructures. Bilancing and Assessing Existing and Alternative Systems)*; netWORKS-Papers 26; German Institute of Urban Affairs (Difu): Berlin, Germany, 2010.
14. Wolf, M.; Störmer, E. Decentralisation of wastewater infrastructure in Eastern Germany. *Netw. Ind. Q.* **2010**, *12*, 7–10.
15. De Graf, R.E. Innovations in Urban Water Management to Reduce the Vulnerability of Cities: Feasibility, Case Studies and Governance. Ph.D. Thesis, Technical University of Den Haag, The Hague, The Netherlands, 2009.

16. Kluge, T.; Libbe, J. (Eds.) *Transformationsmanagement für Eine Nachhaltige Wasserwirtschaft (Transformation Management for Sustainable Water Management)*; German Institute of Urban Affairs (Difu): Berlin, Germany, 2010.
17. Rygaard, M.; Albrechtsen, H.-J.; Binning, P.J. *Alternative Water Management and Self-Sufficient Water Supplies*; IWA-Publishing: London, UK, 2009.
18. Merkel, W.; Bräker, J.; Rohn, A.; Staben, N. Technische Optionen und typische Einsatzbereiche (Datenblätter) (Technical options and typical applications (data sheets)). In *Transformations Management für Eine Nachhaltige Wasserwirtschaft (Transformation Management for Sustainable Water Management)*; Kluge, T., Libbe, J., Eds.; German Institute of Urban Affairs (Difu): Berlin, Germany, 2010.
19. Kluge, T.; Schramm, E. *Wassermärkte der Zukunft: Systemische Innovationen—Weltweit (Water Markets of the Future: Systemic Innovations—Worldwide)*; Ökom-Verlag: Munich, Germany, 2011.
20. Farrelly, M.; Brown, R. Rethinking urban water management: Experimentation as a way forward? *Glob. Environ. Chang.* **2011**, *21*, 721–732. [CrossRef]
21. Sapkota, M.; Arora, M.; Malano, H.; Moglia, M.; Sharma, A.; George, B.; Pamminger, F. An Overview of Hybrid Water Supply Systems in the Context of Urban Water Management: Challenges and Opportunities. *Water* **2015**, *7*, 153–174. [CrossRef]
22. Daigger, G.T.; Crawford, G.V. Enhancing water system security and sustainability by incorporating centralized and decentralized water reclamation and reuse into urban water management systems. *J. Environ. Eng. Manag.* **2007**, *17*, 1–10.
23. Gikas, P.; Tchobanoglous, G. The role of satellite and decentralized strategies in water resources management. *J. Environ. Manag.* **2009**, *90*, 144–152. [CrossRef] [PubMed]
24. Liu, Y.; Giraldo, E.; LeChevallier, M.W. Water reuse in the America's first green high-rise residential building—The Solaire. In *Milestones in Water Reuse: The Best Success Stories*; Lazarova, V., Asano, T., Bahri, A., Anderson, J., Eds.; IWA Publishing: London, UK, 2013; pp. 161–168.
25. Walters, J.; Oelker, G.; Lazarova, V. Producing designer recycled water tailored to customer needs. In *Milestones in Water Reuse: The Best Success Stories*; Lazarova, V., Asano, T., Bahri, A., Anderson, J., Eds.; IWA Publishing: London, UK, 2013; pp. 37–52.
26. Lazarova, V.; Asano, T.; Bahri, A.; Anderson, J. (Eds.) *Milestones in Water Reuse: The Best Success Stories*; IWA Publishing: London, UK, 2013.
27. Gross, A.; Maimon, A.; Alfiya, Y.; Friedler, E. *Greywater Reuse*; CRC Press: Boca Raton, FL, USA, 2015.
28. Brundtland, G.H. *Our Common Future*; Oxford University Press: Oxford, UK, 1987.
29. Bossel, H. *Indicators for Sustainable Development: Theory, Method, Applications*; A Report to the Balaton Group; International Institute for Sustainable Development (IISD): Winnipeg, MB, Canada, 1999.
30. Jörissen, J.; Kneer, G.; Rink, D.; Paskalewa, K. (Eds.) *HGF-Projekt: "Untersuchung zu Einem Integrativen Konzept Nachhaltiger Entwicklung: Bestandsaufnahme, Problemanalyse, Weiterentwicklung" (HGF Project: "Investigation on an Integrative Concept of Sustainable Development: Inventory, Problem Analysis, Further Development")*; Forschungszentrum Karlsruhe, Institut für Technikfolgenabschätzung (ITAS): Karlsruhe, Germany, 1999.
31. Davoudi, A.; Winker, M.; Milosevic, D.; Schramm, E.; Scheidegger, R. *Stoffstromanalyse zu Verschiedenen Wasserinfrastruktursystemen in Frankfurter und Hamburger Quartieren (Material Flow Analysis of Different Water Infrastructure Systems in Quarters of Frankfurt and Hamburg)*; netWORKS-Papers 30; German Institute of Urban Affairs (Difu): Berlin, Germany, 2016.
32. Harting, M. *Wasser-Protest-Marsch—Kritik an der Wasserversorgung für Frankfurt (Water-Protest-March—Criticism of the Water Supply for Frankfurt)*; Frankfurter Allgemeine Zeitung (FAZ): Frankfurt, Germany, 2016.
33. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (DWA). *DWA-A 272 Grundsätze für die Planung und Implementierung Neuartiger Sanitärsysteme (NASS) (Juni 2014) (Principles for the Planning and Implementation of Novel Sanitary Systems (NASS) (June 2014))*; German Association for Water, Wastewater and Waste (DWA): Hennef, Germany, 2014.
34. Stadtentwässerung Frankfurt am Main (SEF). Rein in den Main. Abwasserreinigung in Frankfurt (Pure into the Main. Wastewater Treatment in Frankfurt). Available online: http://www.stadtentwaesserung-frankfurt.de/images/stories/dateien/rein_in_den_main.pdf (accessed on 3 February 2016).
35. Hamburg Wasser. *Umwelterklärung 2010 (Environmental Statement 2010)*; Hamburg Wasser: Hamburg, Germany, 2010.

36. Nolde, E. Die Klima-Positive Recyclinganlage (The Climate-Positive Recycling System). Available online: http://nolde-partner.de/system/files/final_web.pdf (accessed on 2 February 2016).
37. Giese, T.; Londong, J. (Eds.) *Kopplung von Regenerativer Energiegewinnung mit Innovativer Stadtentwässerung—Synthesebericht zum Forschungsprojekt KREIS (Coupling of Regenerative Energy Generation with Innovative Urban Drainage—Synthesis Report on the Research Project KREIS)*; Bauhaus-Institute for Infrastructure Solutions (b.is): Berlin, Germany, 2015.
38. Löw, K. An Innovative Greywater Treatment System for Urban Areas—International Transferability of a German Approach, Installed in GIZ's Headquarters in Eschborn. Master's Thesis, Nürtingen-Geislingen University (HFWU), Nürtingen, Germany, 2011.
39. Kerber, H.; Schramm, E.; Winker, M. *Transformationsrisiken Bearbeiten: Umsetzung Differenzierter Wasserinfrastruktursysteme Durch Kooperation (Dealing with Transformation Risks: Implementation of Differentiated Water Infrastructures through Cooperation)*; netWORKS-Papers 28; German Institute of Urban Affairs (Difu): Berlin, Germany, 2016.
40. Skambraks, A.K.; Augustin, K.; Meinzinger, F.; Hartmann, M. Hamburg's lead on water and energy: Implementing resource-oriented sanitation using the Hamburg Water Cycle. *Water* **2014**, *21*, 15–18.
41. Foxon, T.J.; Mcilkenny, G.; Gilmour, D.; Oltean-Dumbrava, C.; Souter, N.; Ashley, R.; Butler, D.; Pearson, P.; Jowitt, P.; Moir, J. Sustainability Criteria for Decision Support in the UK Water Industry. *J. Environ. Plan. Manag.* **2002**, *45*, 285–301. [CrossRef]
42. Drèze, J.; Stern, N.H. The theory of cost-benefit analysis. In *Handbook of Public Economics*; Auerbach, A.J., Feldstein, M., Eds.; Elsevier Science & Technology: Amsterdam, The Netherlands, 1985.
43. Winker, M.; Schramm, E.; Schulz, O.; Zimmermann, M.; Liehr, S. Integrated water research and how it can help address the challenges faced by Germany's water sector. *Environ. Earth Sci.* **2016**, *75*, 1226. [CrossRef]
44. Hellström, D.; Jeppsson, U.; Kärrman, E. A framework for systems analysis of sustainable urban water management. *Environ. Impact Assess. Rev.* **2000**, *20*, 311–321. [CrossRef]
45. Balkema, A.J.; Preisig, H.A.; Otterpohl, R.; Lambert, F.J.D. Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water* **2002**, *4*, 153–161. [CrossRef]
46. Mysiak, J.; Giupponi, C.; Rosato, C. Towards development of a decision support system for water resource management. *Environ. Model. Softw.* **2005**, *20*, 203–214. [CrossRef]
47. Palme, U.; Lundin, M.; Tillman, A.-M.; Molander, S. Sustainable development indicators for wastewater systems—Researchers and indicator users in a co-operative case study. *Resour. Conserv. Recycl.* **2005**, *43*, 293–311. [CrossRef]
48. Tanyimboh, T.T.; Kalungi, P. Multicriteria assessment of optimal design, rehabilitation and upgrading schemes for water distribution networks. *Civ. Eng. Environ. Syst.* **2009**, *26*, 117–140. [CrossRef]
49. Kodikara, P.N.; Perera, B.J.C.; Kularathna, M.D.U.P. Stakeholder preference elicitation and modelling in multi-criteria decision analysis—A case study on urban water supply. *Eur. J. Oper. Res.* **2010**, *206*, 209–220. [CrossRef]
50. Larsen, T.A.; Maurer, M.; Eggen, R.I.L.; Pronk, W.; Lienert, J. Decision support in urban water management based on generic scenarios: The example of NoMix technology. *J. Environ. Manag.* **2010**, *91*, 2676–2687. [CrossRef] [PubMed]
51. Moglia, M.; Sharma, A.K.; Maheepala, S. Multi-criteria decision assessments using Subjective Logic: Methodology and the case of urban water strategies. *J. Hydrol.* **2012**, *452–453*, 180–189. [CrossRef]
52. Schuwirth, N.; Reichert, P.; Lienert, J. Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater. *Eur. J. Oper. Res.* **2012**, *220*, 472–483. [CrossRef]
53. Behzadian, K.; Kapelan, Z. Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems. *Sci. Total Environ.* **2015**, *527–528*, 220–231. [CrossRef] [PubMed]
54. Lienert, J.; Scholten, L.; Egger, C.; Maurer, M. Structured decision-making for sustainable water infrastructure planning and four future scenarios. *Eur. J. Decis. Process.* **2015**, *3*, 107–140. [CrossRef]
55. Scholten, L.; Scheidegger, A.; Reichert, P.; Mauer, M.; Lienert, J. Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis. *Water Res.* **2014**, *49*, 124–143. [CrossRef] [PubMed]
56. Fishburn, P. *Additive Utilities with Incomplete Product Set: Applications to Priorities and Assignments*; Operations Research Society of America (ORSA): Baltimore, MD, USA, 1967.

57. Zangemeister, C. *Nutzwertanalyse in der Systemtechnik—Eine Methodik zur multidimensionalen Bewertung und Auswahl von Projektalternativen (Cost-Benefit Analysis for Systems Technology—A Methodology for the Multi-Dimensional Evaluation and Selection of Project Alternatives)*; Dissertation u.a. Prüfungsschriften; Wittemann: Munich, Germany, 1976.
58. Triantaphyllou, E. *Multi-Criteria Decision Making: A Comparative Study*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2000.
59. Saaty, T. *The Analytic Hierarchy Process*; McGraw-Hill: New York, NY, USA, 1980.
60. Saaty, T.L.; Vargas, L.G.; Murayama, Y.; Liu, C.; Wang, L.; Yang, A. (Eds.) *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*; Springer: Boston, MA, USA; Berlin/Heidelberg, Germany, 2012.
61. Saaty, T.; Vargas, L.G. *Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks*; Springer: New York, NY, USA, 2006.
62. Lai, E.; Lundie, S.; Ashbolt, N.J. Review of multi-criteria decision aid for integrated sustainability assessment of urban water systems. *Urban Water J.* **2008**, *5*, 315–327. [CrossRef]
63. Felmeden, J.; Michel, B.; Zimmermann, M. *Integrierte Bewertung Neuartiger Wasserinfrastruktursysteme—Bewertungsverfahren, Bewertungskriterien, Räumlicher Bezug (Integrated Assessment of Novel Water Infrastructure Systems—Assessment Methods, Assessment Criteria, Spacial Relations)*; netWORKS-Papers 32; German Institute of Urban Affairs (Difu): Berlin, Germany, 2016.