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Integrated water resources management in cities in the world: Global solutions

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ABSTRACT

Population growth, urbanisation, climate change, biodiversity loss, energy use, water security and ageing infrastructures for water supply and treatment require a thorough understanding of the options available for moving towards sustainable cities. The present study provides an analysis of transformation patterns regarding integrated water resources management (IWRM) of cities across the globe. We evaluate IWRM in 125 cities with 48 mostly quantitative indicators collected for each city by performing a cluster analysis of 6000 indicator scores following the City Blueprint Approach. We distinguish five clusters of cities which show a pattern of problem-shifting, i.e., the shifting of largely preventable water resources problems often in the following sequence: drinking water insecurity, pollution caused by inadequate wastewater treatment, inadequate solid waste management, inaction on climate change adaptation, and resource depletion. A city that can address and solve all these problems can be classified as water-wise. Based on the cluster analysis, seven principles are defined to enable urban areas to become water-wise. Because water takes a central position in the United Nations sustainable development goals (SDGs), and is linked, directly or indirectly, to nearly all SDGs, success in IWRM is an important enabler for the other SDGs.

1. Introduction

As a result of population growth and urbanisation, cities around the world are expanding rapidly, sometimes at extraordinary rates, of up to 8% per year (World Population Review, 2021). The world population is estimated to reach 9.8 billion in 2050 and 68% of the total global population will live in urban areas (UNDESA, 2018). These demographic patterns exacerbated by anthropogenic climate change jeopardise water security. By 2050, urban water demand will increase by 80% (Flörke et al., 2018). Water scarcity is a major concern that impacts the global economy and the livelihood of mankind (UNESCO, 2021). Cities are particularly affected by risks of water scarcity due to diminishing resources and overexploitation, water pollution, flooding and insufficient capacity to finance refurbishment of aging infrastructures (Koop & Van Leeuwen, 2017; OECD, 2015b).

Management decisions in cities on water, waste and climate change typically are short term, reactive and tend to create new problems (Koop, 2019; Peters et al., 2021). As water-related hazards are not evenly distributed across the globe, and vary in time, duration, magnitude and nature (EEA, 2012), cities follow different water management approaches. Their strategies are largely driven by accidents and reactive political decisions. Recent examples include downpours and storm events in Copenhagen, New York City and Mozambique (European Commission Joint Research Centre, 2017; Feingold et al., 2018; Phiri et al., 2021), droughts in Istanbul (Van Leeuwen & Sjerps, 2016), Melbourne (Van Leeuwen, 2017), Cape Town (Madonsela et al., 2019) and large parts of Europe (Toreti et al., 2022). Moreover, extreme heat threatens a large number of cities. The city of Ahmedabad in India provides an illustrative example of these heat-related risks (Aartsen et al., 2018). Another example of water-related urban hazards is land subsidence such as in Jakarta, where parts of the city have sunk below sea level resulting from groundwater overexploitation (Rahmasary et al., 2020). Finally, in many places drinking water quality is threatened by improper disposal of municipal and industrial effluents, municipal

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solid waste (MSW), saltwater intrusion, and pollution from agrochemicals (Azizullaha et al., 2011; Rahmasary et al., 2019; Selvakumar et al., 2017; UNESCO, 2021). These are largely preventable problems. Nevertheless, these preventable problems often determine the adaptation patterns of cities. In order to better understand the impact of water-related hazards on urban patterns of development across the globe, the goal of this paper is twofold:

(1) To provide an empirically-based understanding of water management transformation patterns of cities across the globe. For this, we analyse integrated water resources management (IWRM) in cities using mostly quantitative indicator scores collected for 125 cities. We apply a cluster analysis to identify predominant patterns of urban IWRM development to arrive at a definition of a city that has effectively addressed the main water-related hazards. This is referred to as a water-wise cities, and
(2) To formulate guiding principles to support cities in anticipating patterns of consecutive water-related hazards that our data show.

2. Methodology

2.1. The city blueprint approach

The City Blueprint Approach (CBA; Fig. 1) consists of three complementary frameworks. The main challenges of cities are assessed with the Trends and Pressures Framework (TPF) (Koop & Van Leeuwen, 2021a). The water management performances are assessed with the City Blueprint Framework (CBF) (Koop & Van Leeuwen, 2021b). Where cities can improve their water governance is assessed with the Governance Capacity Framework (GCF). The TPF and CBF evaluate a total of 48 indicators and the GCF addresses 27 governance questions for water-related challenges (Koop & Van Leeuwen, 2021c; Koop et al., 2017). This paper addresses only the TPF and CBF analyses of 125 cities for which 48 indicators were calculated for each city resulting in a total number of 6,000 indicator scores.

2.1.1. Trends and pressures framework

Every city has its own context-specific social, environmental, financial and governance challenges. The TPF addresses these challenges, measured with 24 indicators divided over four categories (Koop & Van Leeuwen, 2021a). The TPF provides the context in which water managers may gain insight on limitations and windows of opportunity for improving IWRM.

Most of the data for the calculation of the indicator scores are obtained from international organisations such as the World Health Organisation, the World Bank, the International Labour Organisation, and the European Environment Agency. Some studies take advantage of 'local' quantitative data from river basin management plans or cities' own knowledge. The score of each of these TPF indicators is calculated from 0 to 10, where a higher score represents a higher urban pressure or concern. The scores of the 24 indicators are displayed in a spider web diagram. The Trends and Pressures Index (TPI) is the arithmetic mean of the 24 TPF indicators. High TPI scores represent high overall concerns

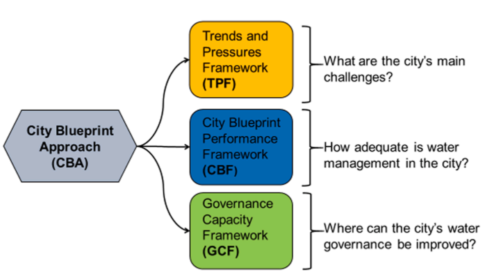

Fig. 1. Overview of the City Blueprint Approach which consists of three complementary assessment frameworks (Koop & Van Leeuwen, 2021 a, b, c).

that can form challenges for a city's IWRM. The indicators, the data sources, calculation methods, sample calculations, and references are provided in Koop & Van Leeuwen (2021a) or directly accessible through the following weblink: https://library.kwrwater.nl/publication/61396712/.

2.1.2. City blueprint framework

The CBF assesses the water management performances of a city and includes aspects such as MSW, climate adaptation and green space. The CBF consists of 24 performance indicators divided over seven categories: (I) basic water services, (II) water quality, (III) wastewater treatment, (IV) water infrastructure, (V) MSW, (VI) climate adaptation, and (VII) plans and actions.

The CBF data are obtained from local authorities using questionnaires and have been critically discussed and reviewed with each city. Each indicator is scored ranging from 0 (poor performance) to 10 (good performance) and displayed in a spider web diagram. Thus, the lower the score of the indicator, the more room there is for improvement (Koop & Van Leeuwen, 2021b). The Blue City Index (BCI) is the geometric mean of the 24 CBF indicators. High BCI scores represent good performance on IWRM. The indicators, the data sources, calculation methods, sample calculations, and references are provided in Koop & Van Leeuwen (2021b) or directly accessible through the following weblink: https://library.kwrwater.nl/publication/61397318/.

2.2. Update of the database of cities

Data using the CBA have been gathered for 125 municipalities and regions in 53 countries over the last decade. In order to consolidate the database and to remove temporal inconsistencies and to further simplify and harmonise the methodology, a review and update took place in 2021. Every effort has been undertaken to verify sources and to find the most recent and reliable information available. During this process the original CBA applied since 2015 has been modified. Details on the consolidation of the database are provided in the Supplementary Information. The update of the database of cities was the first step in the research process summarised in Fig. 2.

2.3. Cluster analysis

Cluster analysis is a procedure for grouping cases (objects of investigation) in a data set. For this purpose, the first step is to determine the similarity (distance) between the cases by a suitable measure. The second step searches for the fusion algorithm which combines the individual cases successively into groups or clusters (Backhaus et al., 2021). In this study, hierarchical clustering was applied to 125 cities using SPSS and the squared Euclidian distance (with squared Euclidean distance $>$ 13.5). This was followed by rearranging the cities according to the clustering after which cluster means and standard deviations were calculated for both the CBF and TPF indicators (see Supplementary Information). For each cluster also the BCI and TPI values were calculated.

3. Results

The results of the cluster analysis are shown in Tables 1 and 2. The

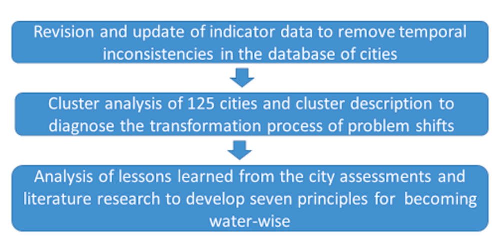

Fig. 2. Schematic illustration of the three research steps adopted in this study.

Table 1
Mean and standard deviation (SD) of CBF indicators and BCI for clusters 1-4 based on the hierarchical clustering as presented in the Supplementary Information.

CBF Indicators	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	(n = 25)		(n = 35)		(n = 33)		(n = 27)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1 Access to drinking water	7.9	2.4	9.8	0.7	9.9	0.2	10.0	0.1
2 Access to sanitation	6.7	3.1	9.3	0.6	9.4	1.2	9.9	0.2
3 Drinking water quality	7.7	2.1	8.6	0.7	9.8	0.9	9.9	0.1
4 Secondary WWT	1.9	1.9	5.6	1.8	9.0	1.3	8.0	0.9
5 Tertiary WWT	0.2	0.7	0.7	2.3	5.3	3.2	8.0	2.0
6 Groundwater quality	5.2	2.8	4.9	2.9	7.0	1.9	8.0	1.9
7 Nutrient recovery	0.0	0.2	0.0	0.0	4.4	4.3	2.8	4.1
8 Energy recovery	0.2	0.5	0.1	0.3	6.6	3.2	6.5	3.9
9 Sewage sludge recycling	1.0	1.4	5.5	3.5	7.4	2.9	8.7	2.2
10 WWT energy efficiency	2.7	2.4	4.2	2.6	7.1	2.0	7.9	2.4
11 Stormwater separation	2.3	2.9	7.5	2.9	4.5	3.6	5.9	2.8
12 Average age sewer	4.5	3.6	8.7	1.8	2.8	2.9	4.6	1.9
13 Water system leakages	3.3	2.7	6.9	1.4	6.2	1.8	8.1	1.8
14 Operation cost recovery	4.1	2.6	5.3	2.7	4.9	2.3	5.7	2.3
15 MSW collected	6.5	2.8	6.7	2.4	3.3	2.2	4.0	1.4
16 MSW recycled	0.8	1.2	0.4	1.4	4.0	2.2	9.0	1.4
17 MSW energy recovered	0.0	0.1	5.2	3.0	1.9	2.5	8.8	1.9
18 Green space	3.1	3.8	4.1	1.5	2.5	1.7	5.3	3.0
19 Climate adaptation	4.8	2.1	8.0	1.2	7.3	2.0	7.6	2.1
20 Climate-robust buildings	3.8	2.1	8.1	1.1	7.1	2.0	7.7	2.1
21 Management and plans	4.9	1.9	9.1	1.0	7.2	2.0	7.6	1.8
22 Water efficiency measures	4.9	1.9	8.4	1.1	7.4	2.0	7.3	2.4
23 Drinking water consumption	9.1	1.0	8.6	1.9	7.8	1.9	8.9	1.6
24 Attractiveness	4.4	2.6	6.9	0.8	7.7	2.1	8.1	1.7
Blue City Index (BCI)	3.6	0.6	4.5	0.4	5.2	0.7	6.8	0.8

Table 2
Mean and Standard Deviation of TPF indicators and TPF for Clusters 1-4 based on the hierarchical clustering as presented in the Supplementary Information.

TPF Indicators	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	(n = 25)		(n = 35)		(n = 33)		(n = 27)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1 Urbanisation rate	4.8	2.9	1.2	1.0	1.9	1.8	1.6	0.7
2 Burden of disease	4.7	2.7	1.0	1.3	2.2	0.8	2.0	0.2
3 Education rate	6.8	2.4	5.1	1.1	2.7	1.8	2.1	1.1
4 Female participation	3.9	1.7	3.2	0.6	3.4	0.7	2.4	0.5
5 Urban drainage flood	8.0	3.3	9.5	2.1	6.1	2.6	4.5	3.0
6 River peak discharges	5.5	4.3	4.0	1.8	5.1	3.3	6.6	3.0
7 Sea level rise	3.3	4.5	0.7	1.8	1.4	2.9	4.3	4.4
8 Land subsidence	4.3	4.4	2.7	2.3	2.0	2.5	2.7	3.0
9 Freshwater scarcity	2.4	2.8	2.3	2.0	3.4	2.1	2.4	2.3
10 Groundwater scarcity	4.1	3.9	1.9	2.0	3.3	2.1	2.0	1.6
11 Sea water intrusion	5.3	4.3	1.6	1.8	2.9	3.4	2.3	3.3
12 Biodiversity	3.3	1.3	1.7	1.9	6.0	2.2	7.6	3.1
13 Heat risk	7.0	3.5	5.8	1.7	6.4	2.6	2.8	2.0
14 Air quality	6.1	3.4	7.1	2.5	3.5	2.3	2.6	1.6
15 Economic pressure	8.9	1.8	3.4	1.8	4.1	2.7	2.0	1.8
16 Unemployment rate	2.5	2.6	0.8	2.2	3.7	2.9	1.8	0.9
17 Poverty rate	2.5	3.2	1.3	0.6	0.1	0.4	0.2	0.7
18 Investment freedom	5.1	1.9	7.6	1.7	2.2	0.8	1.5	0.6
19 Voice and accountability	5.1	1.3	7.8	1.8	3.0	0.8	2.4	1.4
20 Political stability	5.7	1.5	5.3	0.7	4.2	0.9	3.3	0.7
21 Government effectiveness	5.4	1.3	3.9	0.5	2.9	1.0	1.7	0.7
22 Regulatory quality	5.3	1.2	5.3	0.9	2.7	0.9	1.7	0.9
23 Rule of law	5.5	1.2	5.3	1.0	2.9	1.1	1.7	0.9
24 Control of corruption	5.8	0.9	5.4	0.9	3.1	1.3	1.5	1.3
Trends and Pressures Index	5.1	1.0	3.9	0.6	3.3	0.7	2.7	0.6

hierarchical clustering resulted in four clusters of cities; five cities fell outside these four clusters and have not been addressed further. The clusters align with the overall scores of the BCI (Tables 1 and 2). The results show that there is a gradual increase in most CBF indicator scores and BCI values from cluster 1 to cluster 4, reflecting an improvement of IWRM (Table 1). This increase is accompanied by a gradual decrease of the TPF indicator scores and TPI values from cluster 1 to cluster 4 (Table 2), reflecting that these cities also improve on managing their social, environmental, financial and governance challenges. The data of the cluster analysis are presented as spider diagrams in Figs. 3 and 4, respectively.

The cluster analysis reveals that cities across the globe are in different stages of development regarding IWRM (Tables 1 and 2). The following clusters or stages can be discriminated:

Cluster 1 – Water-secured cities. Cities are improving their water security by expanding the limited coverage of drinking water supply and sanitation. Waste water treatment (WWT) is often poor and does not keep up with expanding sanitation and wastewater drainage coverage

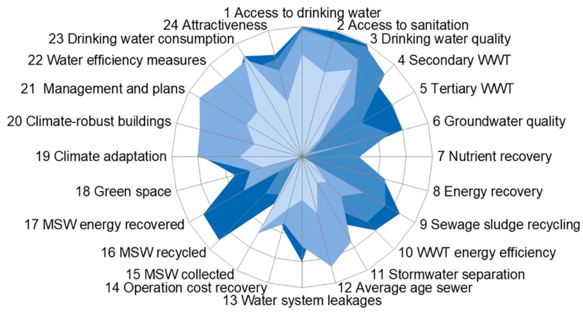

Fig. 3. Summary of the cluster analysis of 125 cities showing the mean values of the 24 CBF indicators for the four observed clusters 1 (light blue) to 4 (dark blue). The CBF indicators are scored on a scale between 0 (poor performance) to 10 (excellent performance). A gradual improvements in water management performance is observed with each consecutive cluster. Further details on the clusters and on each of the 24 CBF indicators for these clusters are provided in Table 1 and the Supplementary Information.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

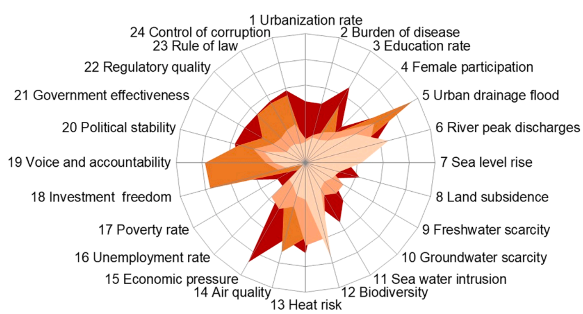

Fig. 4. Summary of the cluster analysis showing the mean values of the 24 TPF indicators for the four observed clusters 1 (dark red) to 4 (pink). The TPF indicators are scored on a scale between 0 (no concern) to 10 (great concern). A gradual decrease in the magnitude of social, environmental, financial and governance challenges is observed with each consecutive cluster. Further details on the clusters and each of the 24 TPF indicators for each cluster are provided in Table 2 and the Supplementary Information.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

leading to greater pollution (Table 1). Cities belonging to cluster 1 generally face high urbanisation rates and burdens of disease and great governance concerns (indicators 19-24) as shown in Table 2. The average water management performances expressed in the BCI for cluster 1 is 2.4 (SD ± 0.6). Overall the limitations for adequate IWRM are substantial. This is evident from a high average TPI of 5.1 (SD ± 1.0).

Cluster 2 – Sewered cities. These cities have improved their quality of and access to drinking water but are confronted with unsolved challenges of MSW and wastewater as untreated sewage and MSW pollute soil, surface water and sediments and groundwater (Tables 1 and 2). Focussing solely on WWT is not effective as solid waste blocks sewer systems and drainage canals, streets are flooded after downpours, and cities with combined sewer overflows pollute surface waters. As a result, critical services such as human health, biodiversity, fisheries, aquaculture, tourism and drinking water quality can be threatened. Consequently, cluster 2 cities tend to prioritise secondary WWT coverage (i.e., reducing chemical and biological oxygen demand at least by 70% and 75% respectively) as well as proper MSW collection and recycling to prevent freshwater and marine pollution (Jambeck et al., 2015; Rahmasary et al., 2020). This is typically done through so-called grey engineering solutions. Although secondary WWT has improved compared to cluster 1, tertiary WWT (i.e., additional treatment step to remove nitrogen, phosphate and micropollutants) remains nearly absent. Cities belonging to cluster 2 have lower urbanisation rates and lower burdens of disease and have slightly improved on governance (Table 2). The average BCI for cluster 2 is somewhat higher than for cluster 1. The BCI is 4.5 (SD ± 0.4) and the TPI is 3.9 (SD ± 0.6).

Cluster 3 – Climate-resilient cities. Extreme weather events, aging infrastructure, limited green space and poor solid waste handling are among the key challenges of cities belonging to cluster 3. These cities have taken steps to achieve full access to basic water services. They collect and treat waste streams (both waste water and MSW) efficiently through grey infrastructure solutions. As such, secondary WWT coverage is strongly improved. However, tertiary WWT remains only partly implemented. Importantly, these cities have not yet appreciated that water plays a key role in the spatial adaptation to climate-related challenges (Koop & Van Leeuwen, 2017). These cities typically rely on quick drainage of stormwater which tend to create urban drainage flooding due to a lack of sufficient water infiltration and water storage capacity. Moreover, the lack of green area results in a high vulnerability to heatwaves and amplifies urban heat islands throughout the city. These cities take actions to become climate-resilient through prioritising spatial incorporation of green and blue infrastructures such as green roofs, bio swales, ponds and parks (Aartsen et al., 2018; Feingold et al., 2018; Madonsela et al., 2019). The average BCI and TPI for cluster 3 is 5.2 (SD ± 0.7) and 3.3 (SD ± 0.7), respectively.

Cluster 4 – Circular cities. After a city becomes climate-resilient, cluster-4 cities increasingly aim for implementing circular solutions to address resource scarcity. Hence, the recovery of energy and resources from waste streams is pursued. This requires substantial capital investments for rebuilding existing wastewater and solid waste treatment facilities that have traditionally been designed with a single purpose: to effectively address pollution (Kehrein et al., 2020; Trimmer et al., 2019; Van Leeuwen et al., 2018). Recovery of energy and resources also require the involvement of other stakeholders, for instance citizens for waste separation, but also for local systems of heating and exploring new markets for the recovered products (Van der Hoek et al., 2017). Full circularity is their goal and options remain to improve on all aspects of water management. These cities generally have lower TPF scores and have greatly improved on all governance indicators (Table 2). The average BCI and TPI for cluster 4 is 6.8 (SD ± 0.8) and 2.7 (SD ± 0.6), respectively.

Cluster 5 – Finally, the fifth and last stage of IWRM of cities is progression towards water-wise cities. Water-wise cities are cities that fully integrate water into urban infrastructure planning and their continued pursuit to improve circularity through involving local communities to promote sustainable integrated decision-making and behaviour. Water-wise cities are largely water self-sufficient, attractive, innovative and circular by applying multiple (de)centralised solutions. For instance, these cities fully apply energy and resource recovery from their waste streams (Koop & Van Leeuwen, 2017; Peters et al., 2021). These cities have successfully addressed all the previously mentioned challenges and as a result have an overall BCI score of 8.0 or higher. Singapore and Amsterdam (Peters et al., 2021) are the only cities among the 125 cities that could be classified as water-wise cities. Water-wise cities are advanced but need to keep water on top of their political agenda as citizens may take high levels of IWRM for granted (Koop & Van Leeuwen, 2021c). Thus, water-wise cities need to have an open mind to explore new opportunities and cost-effective improvements and continue their interaction with all stakeholders (Koop & Van Leeuwen, 2017; Peters et al., 2021).

Figs. 3 and 4 provide a visual representation of the cluster analysis provided in Tables 1 and 2. Fig. 3 shows the average CBF indicator scores for each cluster. We observe that the overall IWRM performance of cities progressively improves from cluster 1 to 4. Providing basic water services (indicators 1, 2 and 3) is the first priority for water-secured cities and the first challenge that is addressed (in cluster 1). Secondary WWT coverage (indicator 4) follows on as this is one of the key priorities for sewered cities (i.e., cluster 2). The focus on climate-resilient cities (i.e., cluster 3) to expand their green space, climate adaptation and climate robust buildings (indicators 18-20) is evident from the scores of these indicators. Next, nutrient recovery and energy recovery (indicators 7 and 8) only improve at a later stage in cluster 4 (i.e., circular cities). Interestingly, an opposite pattern can be observed for drinking water consumption (indicator 23). For water-secured cities this indicator has the highest performance scores since the average consumption is lowest which is partly caused by a low service coverage. Drinking water consumption rapidly increases in sewered cities. In addition, high leakage rates of 20–50% are not uncommon at this stage (indicator 13). Water consumption slowly reduces in cluster 3 and 4 but never returns to the low consumption level observed in cluster 1. Finally, the slow uptake of more advanced solid waste treatment techniques can be observed. These indicators only start to improve once a city is in cluster 4: circular cities.

In addition to the CBF, the complementary TPF assesses the key social, environmental, financial and governance pressures that may limit the ability of local water managers to perform well. Cities performing better on water management (Table 1, Fig. 3) generally face lower social, environmental, financial and governance concerns (Table 1, Fig. 4). Fig. 4 shows that particularly water-secured cities encounter high urbanisation rates, a large burden of disease, limited government effectiveness, as well as economic pressures (indicators 1, 2, 21 and 15). These concerns are decreasing in each consecutive cluster. An opposite pattern can be observed for environmental pressures such as river peak discharges, sea level rise and biodiversity (indicators 6, 7 and 12). Finally, our data suggests that good governance (indicators 19-24) is positively correlated with water management performance as measured by the CBF indicators (Fig. 3).

Finally, Fig. 5 shows the spatial distribution of the clusters of cities. It is important to consider that although we intend to provide a global comprehension of urban water management patterns, our data over-represents cities in Europe and China. It can be observed that most circular cities (cluster 4) are situated in North-western Europe. The variety in urban clusters within Europe also stands out and may represent differences in climate zones and societal developments, particularly after World War II. Sewered cities (cluster 2) are almost exclusively Chinese cities. This may reflect the strongly centralised Chinese system of urban planning. However, beyond these general spatial patterns, it should also be noted that substantial differences between neighbouring cities are frequently observed indicating a large potential of cities to improve their water management despite regional circumstances.

From the five stages that are identified, a general pattern can be observed in which management solutions to one problem lead to a new problem. This pattern can be referred to as problem-shifting (shown in Fig. 6). The key problems – lack of access to basic water services, large-scale water pollution, climate vulnerability and resource scarcity – are challenges that cities need to address.

The literature on sustainability transformations typically define transformation as: “the capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable” (Patterson et al., 2017; Walker et al., 2004). Accordingly, the clusters of cities could be explained as levels of transformation observed across the globe. There might be differences between these transformative changes caused by unpredictable events such as droughts e.g., Melbourne (Van Leeuwen, 2017) and Cape Town (Madonsela et al., 2019), floods as in New York City (Feingold et al., 2018) and Copenhagen (European Commission Joint Research Centre, 2017), and urban heat islands in Ahmedabad (Aartsen et al., 2018). These events often trigger reactive policy responses that can boost alternative paths of urban transformation. Nevertheless, the identified clusters overall illustrate a process of transformation. This transformation is characterised by a process of problem-shifting. The observed transformative stages show a pattern that is largely a result of inadequate management solutions to prior challenges. This problem-shifting pattern is therefore far from ideal. Hence, our results emphasize the need of forward-thinking, with more holistic, long-term planning and data collection to monitor progress of the implementation measures.

The ability of cities in developing countries to transform to water-wise cities will be critical for human health and environmental sustainability as the world progresses into the twenty-first century. This is most relevant for countries facing fast population growth and high rates of urbanisation. Many developing countries in Africa face such developments (Koop & Van Leeuwen, 2017) where water security is broader than the mismatch between supply and demand, and human induced scarcity factors (e.g., inequality, poor governance, weak institutions or imbalanced power relations) are equally important (Chitonge, 2020). Often urbanisation outpaces economic growth (Castells-Quintana & Wenban-Smith, 2020). Increasing urban density may not develop into greater prosperity and well-being, unless appropriate governance structures are developed. This is particularly the case in sub-Saharan Africa where 78% of the residential areas in cities developed between 1990 and 2014 are informal and unplanned, without any water, wastewater and MSW services (Visagie & Turok, 2020).

Combinations of institutions, financing mechanisms and technologies differ from country to country, but all developed countries face similar problems such as: (1) aging infrastructures that need upgrading

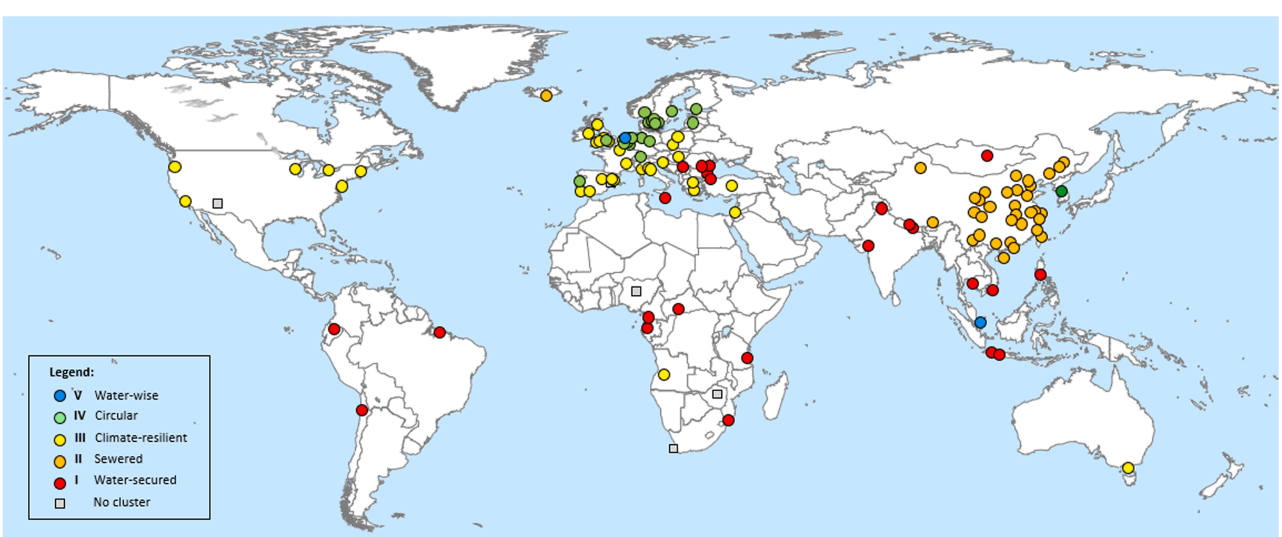

Fig. 5. Global distribution of the 5 identified clusters of cities based on the 125 cities assessed in 53 countries.

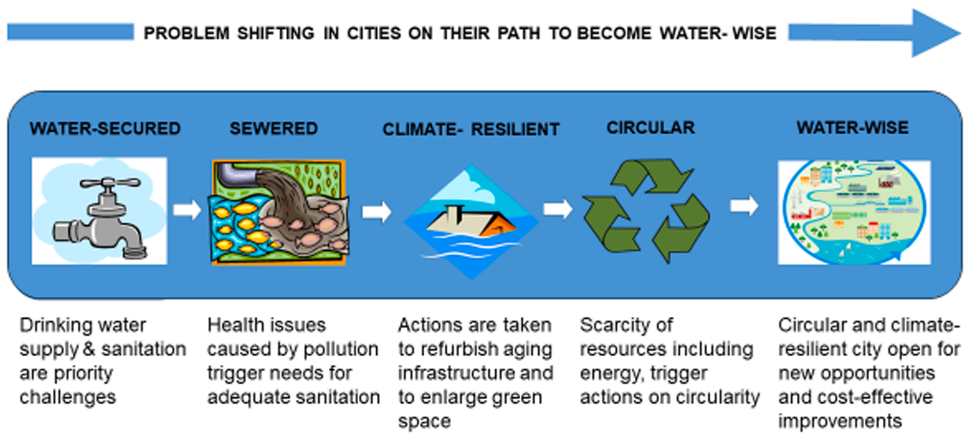

Fig. 6. Simplified scheme of a generic path followed by cities to become water-wise based on the hierarchical cluster analysis of 125 urban water management assessments. Problems are often addressed in the following sequence: drinking water security, wastewater treatment and MSW collection and treatment, climate adaptation and resource recovery.

and in some cases urgently and extensively, (2) implementation of health and environmental standards, diffuse pollution, higher demands and competition for scarce water resources and extreme weather events, (3) "lock-in" situations in technical specific trajectories preventing cost-effective and efficient technical solutions, and most of all governance gaps such as information gaps, sectorial fragmentation and limited resources (Johannessen et al., 2019; Koop et al., 2017; Koop & Van Leeuwen, 2017; OECD, 2014; 2015a). Inadequate governance capacity impedes cities to improve IWRM in an effective manner and delays necessary investments in drinking water infrastructure, sewerage and WWT. This shifts the legacy to next generations. Mounting evidence in water research suggests no reversals in major trends and an expectation that these water problems will intensify if no substantial acceleration will be realised (Pahl-Wostl et al., 2013). The longer political leaders wait, the more expensive and difficult the transformation to sustainable practices will become and the danger to current and future generations and economies will increase (EEA, 2012; Koop & Van Leeuwen, 2017).

4. Discussion

A holistic long-term perspective on how challenges of IWRM unfold and what kind of financial and human resources a city requires in anticipating and adapting to these challenges are essential to facilitate a well-informed inclusive weighing of interests. Projections of global financing needs for water infrastructure range from USD 6.7 trillion by 2030 to USD 22.6 trillion by 2050 (OECD, 2019). The high cost of infrastructure in cities (Swilling et al., 2013), and especially the high cost of water infrastructure (OECD, 2019) and climate adaptation (Swiss Re Institute, 2021) require long-term and consistent planning. Unfortunately, there is no one-size-fits-all solution for cities in the world (Lin et al., 2021). It is more likely that a combination of approaches that are tailored to the specific needs of cities can provide solutions (Koop & Van Leeuwen, 2017). Nevertheless, based on the observed global water management patterns, some general principles may be identified with the intention of enabling cities to identify solution pathways and progress in achieving their ambitions.

4.1. Towards solutions pathways

The observation that cities can be categorised into clusters (Figs. 3 and 5) is also promising as it may lead to an acceleration of improvements as "clusters of solutions" may be possible for cities facing similar challenges. Based on the observed categorisation of cities, seven principles are formulated. These principles are by no means exhaustive but may provide an indication of aspects that - from a holistic urban planning perspective - cannot be disregarded in the global urban endeavour to address water-related challenges. Accordingly, beyond the empirically-based observation in the results section, this discussion section outlines general contemplations on how city planners, practitioners, politicians, but also the scientific community, can contribute to the development of more holistic management solutions and - in doing so - avoid the observed pattern of problem shifting. These contemplations are developed according to three steps:

I Each of the five identified clusters has critical indicators that represent the main focus for these cities. This focus tends to be a logical result of the most pressing challenges that these cities face. However, the selected solutions also tend to be rather narrowly defined, leading to new problems that cities face in the next category. Based on the critical indicators of each of the five categories, a principle for identifying more holistic solutions is provided. In addition, two principles are formulated based on two critical indicators that apply to all categories of urban transformation (Table 3).

II These principles are supported by references of the scientific community and leading international organisations such as the United Nations and OECD.

III Five interviews with experts in the field of global hydrology, wastewater treatment, water technology, microbiology and sustainability have been conducted to enrich the selection and formulation of the principles.

4.2. Seven principles to enhance urban water management transformation

The principles below are intended to provide general guidance on how city planners, practitioners, politicians, but also the scientific community, can contribute to an accelerated transformation towards water-wise cities.

4.2.1. Principle 1 - Water as enabler: explore co-benefits at an early stage

Access to drinking water and sanitation (i.e., Sustainable Development Goal; SDG 6) are key foci for cities in category 1 water-secured cities. However, achieving this objective requires both inclusive and integrated approach where co-benefits are explored. Inclusiveness is important in the 2030 Agenda (UNICEF & WHO, 2019) and commits UN member states "to take bold and transformative steps to shift the world onto a sustainable and resilient path, seeks to realise the human rights of all, to achieve gender equality and the empowerment of women and girls, and ensure no one will be left behind". Integration is critical in achieving SDG6 since water takes a central position in the SDGs and is

Table 3
Link between the urban water management transformation categories, their critical indicators and key problem(s) that form the basis for seven principles that may enable cities to develop more holistic water management solutions.

Transformation category	Critical indicator(s)	Key problem(s)	Principle
I. Water-secured	Access to drinking water; Access to sanitation	Lack of access to safe drinking water and sanitation lead to large-scale health and environmental problems	I. Water as enabler: explore co-benefits at an early stage
II. Sewered	Secondary WWT; Solid waste recycled	Access to sanitation is high but lack of waste water and MSW collection and treatment lead to large-scale pollution	II. Proper solid waste handling is a premise for IWRM
III. Climate resilient	Green space	Technical solutions have addressed large-scale pollution but fail to cover climate adaptation	III. Nature as building blocks for cities
IV. Circular	WWT Energy recovery; WWT nutrient recovery	Climate vulnerability is improved but limited focus on circularity limits resource recovery	IV. Waste is an untapped and valuable resource
V. Water-wise		Local solutions have addressed most issues. However consumption patterns require attention to address global issues	V. Change diets: the protein transition
Apply to all categories	Management and action plans	Lack of city-level action plans impedes holistic water management solutions	VI. Develop a long-term consistent plan for cities
Apply to all categories	Government effectiveness	Lack of sufficient government effectiveness impedes implementation of water management ambitions	VII. Water governance is key

linked, directly or indirectly, to nearly all SDGs including gender equality and peace (Makarigakis & Jimenez-Cisneros, 2019; Essex et al., 2020; Xian et al., 2022). Therefore, if we want to make progress on the major global challenges, water is an important enabler for the other SDGs (Fig. 7).

Water is however not the only political priority at the municipal level. Hence, it is important that co-benefits are explored. At city level this implies that different relevant sectorial agendas for, e.g., ICT (Information and Communications Technology), energy, transport, solid waste, biodiversity (green and blue space), water supply, wastewater, climate adaptation, housing and industrial concentration should be coupled in coherent planning processes. Although water-secured cities face challenges, such an integrated approach would save time, money and ultimately improve the quality of life for citizens. In fact, cities and countries at all stages of urban transformation will need to plan holistically and continue to manage their resources better. These aspects are explained in more detail in Table 2 and Fig. 5 of a review paper on water (Koop & Van Leeuwen, 2017).

4.2.2. *Principle 2 – Proper solid waste handling is a premise for IWRM*

Secondary wastewater treatment and solid waste recycling are key foci for cities in category 2 sewered cities. Improved access to drinking water and wastewater drainage combined with limited wastewater treatment leads to enhanced water pollution (Koop & Van Leeuwen, 2017). Moreover, studies in several cities in Asia (e.g., Chang et al., 2020; Rahmasary et al., 2019; Rahmasary et al., 2020; Van Leeuwen et al., 2016), Africa (Madonsela et al., 2019) and Latin America

Fig. 7. The water-centric 17 Sustainable Development Goals (Makarigakis & Jimenez-Cisneros, 2019) (with permission).

(European Commission Joint Research Centre, 2017; Schreurs et al., 2018) showed the relevance of proper MSW handling to effective IWRM. In 2016, the world generated 242 million tonnes of plastic waste, which is 12% of all MSW (Kaza et al., 2018). When cities and countries rapidly develop without adequate systems in place to collect and manage MSW, investments in IWRM may not be effective because sewers will become clogged.

4.2.3. *Principle 3 – Nature as building blocks for cities*

Enhancing green space is the key focus for cities in category III climate-resilient cities. Previous solutions to enhance access to drinking water and sanitation as well as improved collection and treatment of wastewater and solid waste, typically do not account for green solutions to address climate vulnerabilities such as extreme rainfall, droughts and heatwaves. Urban expansion and densification places blue-green space under stress (Koop & Van Leeuwen, 2021a; 2021c). Moreover, as urban areas are expanding, nature is under greater pressure than ever before (IRP, 2021). Many ecosystems, from tropical forests to coral reefs, have already been degraded beyond repair or are at imminent risk of “tipping points” (Dasgupta, 2021). As biodiversity is directly linked to food and water security, as well as to human health, cities have a role to play in the conservation of biodiversity within the city and its hinterland (Dorst et al., 2019; Well & Ludwig, 2020; Oke et al., 2021).

4.2.4. *Principle 4 – Waste is an untapped and valuable resource*

Energy and nutrient recovery from waste water and solid waste are important foci for cities in category IV circular cities. What holds for MSW (Kaza et al., 2018), also holds for wastewater. According to the UN, globally, 80% of wastewater returns to ecosystems without being treated or reused (WWAP, 2017). More recent research estimates this discharge is ∼ 48% (Jones et al., 2021). Discharge of untreated wastewater is a major threat for ecosystems and human health (Trimmer et al., 2019). Furthermore, wastewater is a valuable resource for water, phosphorous, nitrogen, energy (heat and biogas), other rare materials (Van der Hoek et al., 2017; Van Puijenbroek et al., 2019; Rodriguez & Saltiel, 2020; Van Leeuwen et al., 2018) and even for proteins with a high potential to capture and store carbon dioxide and to recycle nitrogen and phosphorus (Matassa et al., 2020).

In the 125 cities assessed thus far the average nutrient recovery from wastewater is only 18% and energy recovery only 33%. Solid waste recycling (33%) and energy recovery (38%) are somewhat higher. Compact and efficient WWT facilities are viable options for densely populated urban areas (Kehrein et al., 2020; Van Leeuwen et al., 2018).

The transformation to a circular economy and decoupling economic growth from the use of primary water resources requires strategic investments in infrastructure, and also requires policy coherence, coordination and collaboration among stakeholders (Ddiba et al., 2020).

4.2.5. Principle 5 – Change diets: the protein transition

Cities in category V – water-wise cities – have implemented many solutions that have effectively addressed a plethora of water-related challenges. However, beyond these local solutions, many global challenges remain for which these cities can contribute in reducing their environmental impact. A particular water-related challenge is water consumption (and greenhouse gas emission) related to consumption patterns, i.e., dietary choices (European Commission Joint Research Centre, 2017). As such, the OECD emphasizes the relevance of the urban-rural interface and urban-rural partnerships (OECD, 2015b; 2016). Four billion people experience severe water scarcity globally during at least one month per year, while over 500 million face severe water scarcity all year round (Mekonnen & Hoekstra, 2016; Hoekstra & Wiedmann, 2014). Agriculture demand accounts for ~92% of the global blue water footprint. The remainder is shared between industrial production and domestic water supply (Hoekstra, 2014; Hoekstra et al., 2012). From land, energy and climate studies, it can be observed that agriculture (e.g., palm oil), and more specifically the livestock sector, plays a substantial role in deforestation, biodiversity loss, water pollution, water scarcity and climate change (Dasgupta, 2021; Hoekstra, 2014; Jalava et al., 2014). Food systems are responsible for a third of global anthropogenic GHG emissions (Crippa et al., 2021). Large increases in freshwater demand can be expected in the next decades (UNESCO, 2021). These developments are estimated to generate a 40% freshwater supply shortage worldwide by 2030 (2030 Water Resources Group, 2009).

Hence, changing consumption patterns – particularly dietary choices – is critical. Effects of different consumption patterns on water use have been demonstrated in the Urban Water Atlas for Europe (European Commission Joint Research Centre, 2017), where water consumption is reported for each city for different types of diets. Furthermore, the FAO (2014) estimates that each year, approximately one-third of all food produced for human consumption in the world is lost or wasted. So, changing diets and minimising food waste provide options for improvement that cities can pursue.

4.2.6. Principle 6 – Develop a long-term consistent plan for cities

The most important lesson from the cluster analysis is the cascade of preventable problems by short-term reactive solutions to problems, i.e., problem-shifting (Koop, 2019) as described in Fig. 6. Cities will need to develop long-term plans for water security. The indicator that assesses the management and actions plans for improved water management (indicator 21) shows a positive correlation ($r = 0.61$) with the overall performance of the other 23 City Blueprint indicators. Such plans were largely lacking, for instance, in Melbourne (Van Leeuwen, 2017), Sao Paulo (Millington, 2018) and Cape Town (Madonsela et al., 2019). By drastically cutting their water use, Cape Town residents and farmers were able to push back "Day Zero" until the rains came, but this showed just how precarious water security can be. Two-thirds of Earth's land is on pace to suffer freshwater scarcity as the climate warms becoming a major problem for people, crops, forests and ecosystems (Pokhrel et al., 2021).

Often, politicians respond rapidly to accidents and incidents, rather than preventing crises that unfold over decades. The obvious explanation for this is that the in-office times of politicians (4 to 5 years in general) do not match the needs of cities (Koop & Van Leeuwen, 2017), which implies that short-termism often dominates long-term interests. The pattern observed (Fig. 6) resembles that of the retrospective analysis of the city of Amsterdam (Peters et al., 2021). This retrospective study started in 1672 and shows that developments in water infrastructure and water management have often been reactive in response to various crises. The example of Amsterdam shows that it is feasible to improve IWRM in decades provided that there is a clear political will to develop long-term plans and actions as well as sufficient resources to execute these plans.

4.2.7. Principle 7 – Water governance is key

To tackle the challenges of IWRM in cities, long-term consistent plans are necessary. However, water governance can be considered as key in the development and implementation of these ambitions. The positive correlation ($r = 0.81$) between the Blue City Index and government effectiveness (TPF-indicator 21) illustrates that cities with higher management performances are associated with higher quality of public services, policy formulation and implementation.

The OECD (2015b) adopted the following definition of water governance: "the range of political, institutional and administrative rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management". Water governance covers the mechanisms, processes and institutions by which all stakeholders – government, the private sector, civil society, pressure groups – on the basis of their own competences, can contribute their ideals, express their priorities, exercise their rights, meet their obligations and negotiate their differences (Koop & Van Leeuwen, 2017). In a feature paper by the OECD (Romano & Akhmouch, 2019) it was concluded that cities must ensure that institutional frameworks in place are "fit to fix the pipes". The biggest challenges, according to the OECD (OECD, 2011; 2015a; 2015b; 2016), are institutional fragmentation, ambiguous legislation, poor implementation of multi-layered governance, as well as matters such as limited capacity at local level, unclear allocation of roles and responsibilities, fragmented financial management, uncertain allocation of resources, and corruption. Hence, water challenges could be mainly characterised as water governance challenges.

5. Conclusions

The sustainable development of cities is threatened by a worldwide water crisis. In order to better understand the impact of water-related hazards on urban patterns of development across the globe, the goal of this paper has been to develop:

i An empirically-based understanding of water management transformation patterns of cities across the globe.
ii Guiding principles to support cities in anticipating patterns of consecutive water-related hazards that our data show.

Based on a cluster analysis of 6000 IWRM indicator scores collected for 125 cities, five clusters have been distinguished. These clusters may be viewed as five subsequent stages of IWRM development. We observe a trend of problem-shifting as a global phenomenon in cities. The key problems – being a lack of access to basic water services, large-scale water pollution, climate vulnerability and resource scarcity – tend to be a result of an incomplete solution to a previous problem. The observed patterns may provide a more profound insight into long-term patterns of urban water management. Additionally, it intends to enable water managers to learn from other cities and develop solutions that limit the (unintendedly) creation of new problems.

In order to escape the observed global pattern of problem-shifting, seven principles are contemplated to enable cities at each category of development to formulate more holistic and proactive solutions. City-scale action plans seem essential. However, good governance could be considered as key to implement these plans. Such a strategic refocus also requires higher priority and funding for capacity development, implementation and monitoring of the SDGs at national levels across the globe (Bierman et al., 2022) as only 42% of the 92 environment-related SDG indicators have sufficient data to assess progress made in achieving the targets (UNEP, 2021)

Author contributions

S.K. and K.v.L. designed the study, S.K. performed the cluster analysis. K.v.L and C.G. drafted the manuscript and further analysed the cluster analysis. S.E. and J.H. reviewed the manuscript. All authors discussed the results and contributed to the manuscript.

Declaration of Competing Interest

The authors hereby state that there is no conflict of interest.

Data availability

The authors declare that all the data supporting the findings of this study are included in the Supplementary Information.

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Supplementary materials

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