

#### Appendix A.4: Assessment of Sustainable Management Based on CPA

**Water resources:** Sustainable management of water resources aims to minimize water and ecological footprints, as well as the urban water reach, to protect ecosystems, and to maximize the fraction of recycled water and renewable energy used in the urban metabolism:

1) The national water footprint accounts provided by Mekonnen and Hoekstra (2011) include blue (surface and groundwater), green (rainwater stored in or evaporated from soils and plants) and greywater produced by domestic water use (amount of water required to assimilate pollutants to meet specific water quality standards; excludes greywater produced from industry and agriculture) (96). The national water footprint accounts differentiate between internal and external water footprints based on the idea of virtual water, which is water embedded in products and can therefore "virtually" be transported from one country to another in the form of products. Internal water is the water consumed or used to produce goods within a country. External water is the net imported virtual water to meet demands at national level. These accounts have been broken down to the urban scale for some cities (97), but data does not yet cover large numbers of cities. However, because the majority of production from rural areas is consumed in cities and footprints reach well beyond urban boundaries, national assessments are considered good approximations for cities. The water footprint (WFP [-]) includes the total national water footprint [ $\text{m}^3\text{cap}^{-1}\text{y}^{-1}$ ] of all three categories (consumption, production, and external) (96). Local management sustainability considers the internal water footprint ( $\text{WFP}_{\text{internal}}$ ) and is normalized to the maximum of the sample for comparison purposes. Global management sustainability considers the external water footprint ( $\text{WFP}_{\text{external}}$ ).

2) The ecological footprint (EF) measures the ecological assets that a given population requires to produce the natural resources it consumes and to absorb its waste (7). It includes plant-based food and fiber products, livestock and fish products, timber and other forest products, space for urban infrastructure, as well as carbon emissions. The ecological footprint is quantified at a national level in units of global hectares per capita, which is the space consumed per person based on global average productivity of one hectare of land. The ecological footprint presents an absolute value and is commonly compared to national biocapacity, which is the available capacity of land. Global biocapacity currently lies at 1.7 global hectares per person. The ecological footprint metric (EFP) presented here is in multiples of global biocapacity that a country overshoots or underscores:

$$EFP = \frac{EF}{BC} \quad (\text{A.4.1})$$

3) The distance a city reaches into its hinterland to meet the demand for water resources is an indicator of the potential of emerging conflict for water resource competition. Conflict can emerge among different urban areas, urban and rural populations, between sectors, such as urban and agricultural water needs, or between human and ecosystem requirements (22, 48). The idea behind this indicator is similar to the "urban water footprint" (97, 98), but it quantifies the actual distance of water exploitation. Data provided by McDonald et al. (73) of urban water sources and city locations is used to calculate urban water reach. Urban water distance (WD [-]) is the normalized per capita, calculated by summing up the distance [km] between cities and their water sources (surface, groundwater, desalinated water), dividing it by the number of urban population and normalizing it to the maximum.

4) The fraction of water supplied that is sourced from recycled wastewater or desalinated water (RD) increases a city's sustainability by reducing the need for exploiting freshwater sources.

5) The fraction of renewable energy used in the water sector (RE) increases a city's sustainability. This energy can be directly sourced from wastewater in the form of heat or natural gas<sup>1</sup> (methane), or produced from water (hydropower), wind or solar, or from burning waste material. The sustainability of using crops for bioenergy production is questionable given the energy- and water-intensity of growing crops, soil and water pollution resulting from the use of fertilizers and pesticides, and competition of cropland area used for bioenergy instead of growing food (99, 100), and is not considered as a sustainable management option here.

6) The Environmental Performance Indicator (EPI) (101) is a governance indicator that gauges the achievement of established environmental policy goals towards environmental health and ecosystem vitality. The EPI consists of 24 weighted performance indicators regarding policy implementation in ten categories, which pose threats to human health, natural resources and ecosystem services. They include air quality, water and sanitation, heavy metals, biodiversity and habitat, forests, fisheries, climate and energy, air pollution, water resources, and agriculture. The EPI is assessed at the national level in 180 countries and uses a mix of data sources, including, but not limited to, monitoring data, research outputs, surveys and questionnaires, and government statistics (101). National EPI scores are min-max normalized [-].

Sustainable management of water resources is calculated as:

$$M_{Wlocal} = \frac{(1-WFP_{internal})+(1-WD)+RD+RE+EPI}{5} \quad (A.4.2)$$

$$M_{Wglobal} = 1 - \frac{EFP+WFP_{external}}{2} \quad (A.4.3)$$

Global capacities of WFP and WD remain inconclusive (e.g., a “hydrocapacity” of  $X \text{ m}^3\text{cap}^{-1}\text{y}^{-1}$ , comparable to a global biocapacity of 1.7 global hectares in 2018). Planetary boundaries have been proposed for freshwater and nutrient loading, respectively (5, 102–104), with the freshwater planetary boundary determined at  $4000 \text{ km}^3\text{yr}^{-1}$ , resulting in a per capita blue water capacity of  $526 \text{ m}^3\text{yr}^{-1}$  (102). However, two aspects make a comparison with the WFP used here difficult: First, blue water refers to consumptive use of freshwater, only, and it is not integrated with the water quality boundaries; second: There is debate on how to calculate consumptive metrics (102, 104). Also, such calculations seem ambiguous, considering that deforestation counts as “credit”, decreasing consumptive use, although the water “saved” from evapotranspiration will lead to faster runoff, and thus, loss of freshwater discharged into the sea. Therefore, converting green water (stored in forests) into blue water (available in rivers and reservoirs) produces a temporal tradeoff, where the short-term “gain” of blue water resulting from deforestation is lost in the long-term due to reduced retention capacity in the catchment and risk of desertification. Therefore, absolute sustainability measures cannot be assigned here. An upper limit is also difficult to define because with adequate technology large supplies of water can be produced by, e.g., desalination. However, external effects on air pollution, greenhouse gas emissions, and marine ecosystems due to high energy demand and the discharge of refuse brines, as well as being economically unfeasible for

---

<sup>1</sup> Not to be confused with fractured gas extracted from geological formations by fracking technology. This gas is also commonly referred to as “natural gas” which leads to the false idea that this is a renewable or sustainable energy source.

uses such as agricultural irrigation limit the potential for water production (105, 106). A lower limit for WFP could be determined, if recycling was maximized. For lack of a global "hydrocapacity" relative to the WFP, it is unclear whether cities "overshoot" such a sustainability threshold, and therefore WFP (and WD) do not provide absolute measures of sustainable management. However, it allows comparison of footprints across cities. Although water footprints are relative, for calculating  $M_{Wglobal}$  I assume externalized water footprints to have negative impacts (second term in Eq. 2.5 is subtracted from 1).

**Infrastructure:** Sustainable management of infrastructure aims to minimize negative impacts on the environment through pollution, or other types of footprint, which can be minimized through integrated, water-sensitive design. Sustainable management of infrastructure ( $M_I$ ) is calculated as the average of the three metrics:

1) The fraction of wastewater that is treated (WWT) is an indicator of the potential pollution and health threats due to lack of hygiene. This is particularly important in a long-term perspective, as untreated domestic waste seeps into the soil, eventually contaminating ground- and surface waters.

2) The degree of modularity ("decentralization", DC) is a measure of a city's adaptability and flexibility to respond to changing demands and environmental conditions. While a well-maintained, mapped, and mature (i.e., no significant growth) centralized infrastructure is easier to manage than a decentralized or modular infrastructure, modular infrastructure has the advantage of being adaptable to changing demands, avoiding legacy-effects and lock-in, and thus allows easier implementation of innovations at modular scale (20, 107).

3) Integration of infrastructure (II) serving water supply, sanitation and drainage (flood control), the production of energy from waste (-water), the use of treated wastewater for supplying urban waterways and greening, as well as for agricultural irrigation are steps towards water sensitive cities that are based on thinking urban material flows as life cycles of water, nutrients and energy in a nexus of water, food and energy (29, 95, 108, 109). The integration can be implemented at different scales, either at local residential scales where greywater from washing dishes and showering are reused for toilet flushing and garden irrigation, or at neighborhood or city-scale where water of different qualities is reused and provided for different purposes. Integration is determined as the average sum of five metric scores using a binary scoring system (1=present, 0=absent) as presented in **Table A.4.1**.

**Table A.4.1:** Assessment of integration with water supply infrastructure.

Metric	Score
Population covered by sanitary infrastructure >85%	(1/0)
Use of drainage water and treated wastewater for secondary purposes (urban greening, agricultural irrigation, etc.)	(1/0)
Energy production from wastewater and/or waste	(1/0)
Reuse of nutrients contained in sewage sludge	(1/0)
Use of solar heat for warm water production	(1/0)
Infrastructure integration (II):	$\Sigma(\text{scores})/5$

**Financial capital:** The recovery of costs is essential in maintaining a functioning urban water system. If costs are not recovered, the system either relies on permanent financial subsidies, making it vulnerable to subsidy withdrawal, or is prone to degradation due to a lack of funds. Cost recovery (CR) is assessed using a binary score, where CR=1 if cost recovery >90%, and CR=0 if recovery  $\leq$ 90%. International financial assistance (Official Direct Assistance, ODA) and net Foreign Direct Investment (FDI) measure assistance or investment of foreign countries into a nation's economic development. FDI is measured in terms of assets and liabilities as net Balance of Payments (BoP). Divided by a country's Gross National Income (GNI), the sum of ODA and FDI indicate a nation's dependence on foreign economic decisions. As long as financial commitment is maintained, this can have a positive impact on a country's economy in the short term. However, assessments of long-term economic impacts are mixed (110–112), and donor and investor withdrawal can have devastating impacts in the long-term, as cost-intensive construction and maintenance of infrastructure cannot be guaranteed (113–115). The Financial Dependence Metric (FDM; virtually a "financial footprint") is calculated as:

$$FDM = \frac{FDI+ODA}{GNI} [-] \quad (A.4.4)$$

where FDI, ODA and GNI are in [US\$ capita<sup>-1</sup>].

$$M_F = \frac{1-FDM+CR}{2} \quad (A.4.5)$$

Data for ODA and GNI are for 2015 or most recent available data, FDI are averaged over the period 2011-2015. Equivalent indicators to ODA and FDI exist for water sector budgets, in the form of loans and grants provided to the water sector, and can be calculated as fractions of total water sector budget, and divided by total urban population. Again, due to the long-term perspective and resulting interactions among sectors and spatial scales in the sustainability assessment performed here, as well as due to the ease of data access, I assume national level data to be adequate for this purpose.

**Management power:** Sustainable management requires adequate mechanisms of governance and power exertion that allow coordinated and responsive action. Sustainable management power ( $M_M$ ) is calculated as the average of three metrics:

1) Centralization of information (CI): For a smooth operation of services, access to data, information across sectors and scales is necessary, which requires a centralized information management. This is the basis for coordinated management (see below). I use a rating score (0-1) to assess centralization.

2) Coordinated management (CM): For sustainable urban development, all sectors concerned with and impacted by spatial planning should be coordinated (95). Besides the obvious sectors of sanitation,

drainage, energy and urban mobility, additional examples include recreation and urban livability, making land used for water management purposes accessible to the public. Sectors to be considered are shown in in **Table A.4.2**.

**Table A.4.2:** Assessment of inter-sector coordination.

Water supply sector coordination with:	Score
sanitation	(1/0)
drainage	(1/0)
energy and industry	(1/0)
traffic and urban mobility	(1/0)
recreation	(1/0)
urban agriculture	(1/0)
amenities planning	(1/0)
education	(1/0)
Coordinated management, CM:	$\Sigma(\text{scores})/8$

3) Participatory management (PM): Residents and water users should have the possibility to raise their voice and make their concerns heard. Customer service response, public participation events, and other feedback and interaction mechanisms are among the tools to engage in participatory management. Participatory governance has been shown to improve resilience and sustainability (89, 116, 117). I use binary scores to assess participatory management.

**Community adaptation:** Sustainable management of community adaptation relates to the community's engagement, demand management and awareness (118). It also includes its access to safe modes of family planning, and equal economic opportunity through limiting income inequality. Conventional urban water supply systems are characterized by a full externalization of services to a water utility, which attempts to maximize supply in order to meet unconstrained demand.

1) Community engagement in maintenance of services (EM): Even if the provision of services is the responsibility of a professional company, the community should be engaged in service maintenance in the form of sustainable behavior and awareness raising (119). This can be achieved by making service provision visible to citizens, e.g., in the form of storage reservoirs, water filtration ponds, wetlands and green spaces serving as catchment areas, which are accessible for recreation and human mobility such as bicycle and walkways along waterways and other land, or making land available for community use, such as community gardens or environmental awareness projects (120). Opening up land used for urban water management to the public requires awareness and sustainable behavior (e.g., avoidance of littering). Such "shared pathways" can be found in cities working towards becoming water-sensitive (e.g., Melbourne, Singapore, Berlin) (120–122).

2) Demand management (DM) takes the form of passive demand management through installation of water-saving devices (low-flow and pressure-regulated taps and shower-heads, water-saving toilet flushing, etc.) (123). Demand management actively prepares the community for dealing with variations in water services, for buffering periods of drought, and for reducing demand as necessary. Temporary water-saving is required during drought (e.g., Cape Town since 2017, Melbourne 1997-2010, Western United States since 2011), and permanent water-saving is required in water-scarce regions (e.g., Jordan) (59). The latter requires community awareness.

3) Community awareness ("water literacy", AM): Makes sure that citizens are aware of where water is extracted from, how it is processed, how to protect and save water and behave sustainably (124, 125). In some cases, the water utility directly engages in school programs (e.g., Melbourne, Berlin), or the media (Singapore). Awareness-raising can also be achieved through advertisement and community engagement launched through the government, or non-governmental organizations.

4) The Gini coefficient of household income is a measure of income inequality. A high Gini coefficient indicates that average standards are achieved to the benefit of a minority of the population, while the majority lives well below the average. Taking into account inequality for the sustainability of water security and resilience is important, as persistent inequality can erode the security and resilience of certain groups of society, and eventually of society as a whole with consequences to social instability (126). Gini coefficients are reported regularly at the national level by the World Bank. Given the long-term character of sustainability assessments, and cross-scale interactions that can play out over long time-scales, I assume national data to be adequate here. The Gini coefficient of income takes values between 0-1, where Gini = 0 indicates complete equality, while a Gini = 1 indicates complete inequality.

5) The fraction of a nation's population using contraceptive measures is used to estimate a community's access to birth control measures and information aiming to control population growth. Data is taken from (127).

Binary scores are used to assess the first three of the five metrics. Local sustainable management of A ( $M_{Alocal}$ ) is calculated as the average of the first four indicators, while global ( $M_{Aglobal}$ ) is the fifth metric.

Aggregating the sustainable management indicators results in:

$$MP_{local} = \frac{M_{Wlocal} + M_I + M_F + M_M + M_{Alocal}}{5} \quad (A.4.6)$$

$$MP_{global} = \frac{M_{Wglobal} + M_{Aglobal}}{2} \quad (A.4.7)$$

**Table A.4.3:** Data for sustainable management assessment of seven case studies.

<b>Management Portfolio</b>										
<b>W</b>	<b>EFP</b>	<b>WFP<sub>global</sub></b>	<b>MW<sub>global</sub></b>	<b>EPI</b>	<b>WFP<sub>local</sub></b>	<b>1-WD</b>	<b>RD</b>	<b>RE</b>	<b>MW<sub>local</sub></b>	<b>M<sub>w</sub></b>
Melbourne	5.47	0.11	-1.79	0.74	1.00	0.81	0.17	0.47	0.44	-0.68
Berlin	3.12	0.01	-0.56	0.78	0.10	0.95	0.40	0.22	0.65	0.04
Singapore	4.71	0.00	-1.35	0.64	0.00	0.92	0.30	0.00	0.57	-0.39
Amman	1.24	0.05	0.36	0.62	0.05	0.79	0.20	0.00	0.51	0.44
Mexico City	1.71	0.01	0.14	0.60	0.21	0.94	0.20	0.00	0.51	0.32
Chennai	0.71	0.00	0.65	0.31	0.16	0.91	0.26	0.15	0.49	0.57
Ulaanbaatar	3.59	0.60	-1.09	0.58	0.56	0.94	0.00	0.00	0.39	-0.35
<b>I</b>	<b>WWT</b>	<b>DC</b>	<b>II</b>				<b>MI</b>			
Melbourne	1.00	0.00	0.80				0.60			
Berlin	1.00	0.00	0.80				0.60			
Singapore	1.00	0.00	0.40				0.47			
Amman	0.78	0.00	0.20				0.33			
Mexico City	0.10	0.00	0.40				0.17			
Chennai	0.60	0.50	0.00				0.37			
Ulaanbaatar	0.50	0.50	0.00				0.33			
<b>F</b>	<b>CR</b>	<b>1-FDM</b>				<b>MF</b>				
Melbourne	1.00	0.97				0.98				
Berlin	1.00	1.01				1.01				
Singapore	1.00	0.91				0.95				
Amman	0.00	0.89				0.45				
Mexico City	0.00	0.98				0.49				
Chennai	0.00	0.99				0.49				
Ulaanbaatar	0.00	0.76				0.38				
<b>P</b>	<b>GC</b>	<b>CM</b>	<b>PM</b>				<b>MP</b>			
Melbourne	1.00	0.75	1.00				0.92			
Berlin	1.00	0.50	0.00				0.50			
Singapore	1.00	0.63	1.00				0.88			
Amman	0.00	0.13	0.00				0.04			
Mexico City	0.00	0.25	0.00				0.08			
Chennai	0.00	0.00	0.00				0.00			
Ulaanbaatar	0.50	0.25	0.00				0.25			
<b>A</b>	<b>EM</b>	<b>DM</b>	<b>AM</b>	<b>1-Gini</b>	<b>Birth contr.</b>	<b>M<sub>A</sub>_local</b>	<b>M<sub>A</sub>_global</b>	<b>M<sub>A</sub></b>		
Melbourne	1.00	1.00	1.00	0.65	0.71	0.91	0.71	0.81		
Berlin	0.00	1.00	1.00	0.68	0.66	0.67	0.66	0.67		
Singapore	1.00	1.00	1.00	0.54	0.53	0.89	0.53	0.71		
Amman	0.00	0.00	1.00	0.66	0.41	0.42	0.41	0.41		
Mexico City	0.00	0.00	0.00	0.56	0.66	0.14	0.66	0.40		
Chennai	0.00	1.00	1.00	0.65	0.49	0.66	0.49	0.58		
Ulaanbaatar	0.00	1.00	1.00	0.68	0.61	0.67	0.61	0.64		
<b>MP</b>	<b>MP<sub>local</sub></b>	<b>MP<sub>global</sub></b>	<b>MP</b>		<b>FP<sub>global</sub></b>	<b>CP</b>	<b>RP</b>			
Melbourne	0.77	-0.54	0.12		1.54	1.24	0.94			
Berlin	0.69	0.05	0.37		0.95	1.04	0.84			
Singapore	0.75	-0.41	0.17		1.41	0.94	0.84			
Amman	0.35	0.38	0.37		0.62	0.51	0.53			
Mexico City	0.28	0.40	0.34		0.60	0.32	0.47			
Chennai	0.40	0.57	0.49		0.43	0.25	0.36			
Ulaanbaatar	0.41	-0.24	0.08		1.24	0.27	0.45			

**Table A.4.4:** Data used as input to the ternary diagram (Fig. 6).

<b>Input Ternary Diagram</b>							
<b>City</b>	<b>CP</b>	<b>CT</b>	<b>MP</b>	<b>sum</b>	<b>CP<sub>norm</sub></b>	<b>CT<sub>norm</sub></b>	<b>MP<sub>norm</sub></b>
Melbourne	1.24	1.00	0.00	2.24	0.55	0.45	0.00
Berlin	1.04	0.96	0.05	2.04	0.51	0.47	0.02
Singapore	0.92	0.95	0.00	1.87	0.49	0.51	0.00
Amman	0.51	0.81	0.37	1.69	0.30	0.48	0.22
Mexico City	0.38	0.68	0.39	1.45	0.26	0.47	0.27
Chennai	0.25	0.00	0.57	0.82	0.31	0.00	0.69
Ulaanbaatar	0.27	0.56	0.00	0.83	0.33	0.67	0.00
Amman+A	0.76	0.90	0.37	2.04	0.37	0.44	0.18
Mexico City+A	0.59	0.87	0.39	1.85	0.32	0.47	0.21
Chennai+A	0.78	0.78	0.57	2.14	0.37	0.37	0.27
Ulaanbaatar+A	0.47	0.70	0.00	1.17	0.40	0.60	0.00
Melbourne_local	1.24	1.00	0.77	3.01	0.41	0.33	0.26
Berlin_local	1.04	0.96	0.69	2.68	0.39	0.36	0.26
Singapore_Local	0.92	0.95	0.75	2.62	0.35	0.36	0.29
Amman_local	0.51	0.81	0.35	1.67	0.31	0.49	0.21
MC_local	0.38	0.68	0.28	1.34	0.28	0.51	0.21
Chennai_local	0.25	0.00	0.41	0.66	0.38	0.00	0.62
UB_local	0.27	0.56	0.40	1.23	0.22	0.45	0.33