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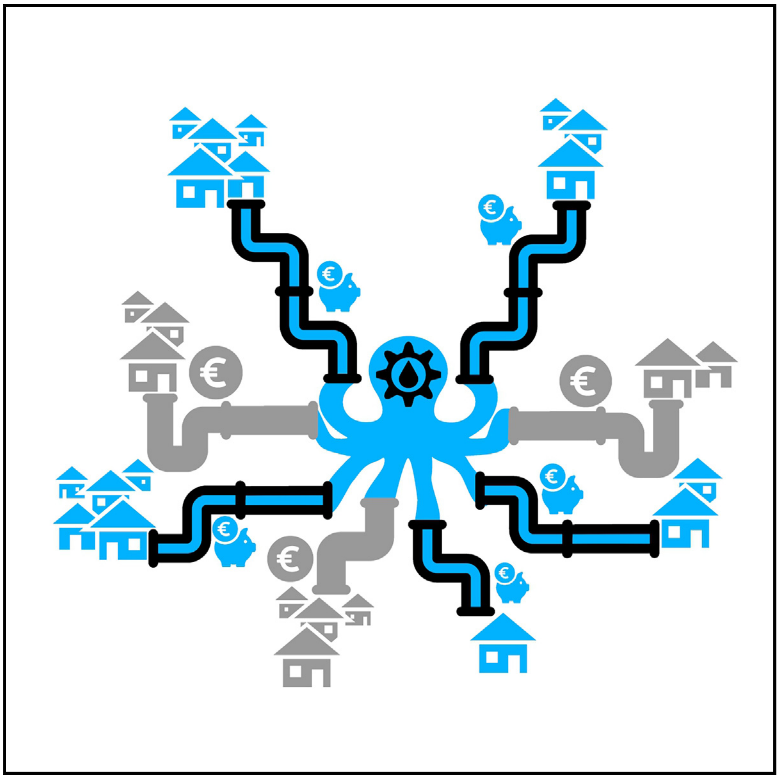
"OCTOPUS" principle reduces wastewater management costs through network optimization and clustering

Graphical abstract



Highlights

- OCTOPUS estimates cost savings for wastewater treatment plant (WWTP) clusters
- 20% of all regions analyzed could save more than 10% through WWTP clustering
- We utilize a graph-based greedy clustering approach
- Local application of OCTOPUS can enhance planning efforts to meet SDG 6

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In brief

Safe water and sanitation are basic human rights (UN Goal 6). However, over half of global wastewater is untreated, harming the environment and public health. Limited investment in infrastructure, especially in emerging nations, is an issue. Our solution, OCTOPUS, merges water treatment systems in communities to cut costs. Results for 140 countries shows potential >10% cost savings in 20% of all regions. OCTOPUS aids economically challenged countries in achieving safe access to water and sanitation.

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“OCTOPUS” principle reduces wastewater management costs through network optimization and clustering

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SCIENCE FOR SOCIETY Safe access to water and sanitation is a basic human right and is set as the United Nations Sustainable Development Goal 6. However, more than half of global wastewater is not treated, thus polluting the environment and posing a health risk to society. Cost is a significant barrier to water treatment in many emerging economies because of the building and maintenance expenses of treatment facilities. We present a novel approach that reduces wastewater management costs by merging water treatment systems of individual settlements into larger networks: an “OCTOPUS” design. Given the limited economic resources in many countries with low wastewater treatment, OCTOPUS helps to better plan and realize safe access to water and sanitation.

SUMMARY

Sanitation and wastewater management are integral to the United Nations Sustainable Development Goal 6 (SDG 6: clean water and sanitation). However, a significant portion (50%–80%) of global wastewater is currently being discharged without proper treatment. A main hurdle in wastewater management are the substantial costs required to achieve SDG 6 that constitute both of the investment costs but also the long-term operation and maintenance costs of treatment facilities. To realize safe sanitation across the globe, we developed the OCTOPUS design that identifies settlement groups where individual treatment plants are merged into a large one. This merging can lower the actual treatment costs. To gauge the global impact, we applied OCTOPUS to over 4.1 million settlements across 140 countries, encompassing more than 2,600 administrative regions. The results demonstrate that over 20% of these regions could achieve cost savings exceeding 10% compared to the conventional approach of having a single treatment plant per settlement.

INTRODUCTION

Sanitation and wastewater management constitute a central part of the United Nations (UN) Sustainable Development Goal 6 (SDG 6).[1] Although, envisioned to be achieved by 2030, the current status of SDG 6 is still looking bleak. As of 2020, 3.6 billion people lacked safely managed sanitation services,[2] the majority of which is located in emerging countries. Global estimates indicate that around 50%–80% of household wastewater is untreated.[3,4] For rural regions, due to a lack of investment and research, the situation is considerably worse.[5] Major bottlenecks that prevent a timely achievement of SDG 6 are governance and financial aspects.[6] Thus, despite governance and administrative hurdles, meeting SDG 6 depends on considerable investment. To obtain a chance of fulfilling SDG 6, the most appropriate and cost-effective wastewater management solutions need to be identified.

Wastewater management can be achieved by central and decentral approaches. Traditionally urban wastewater management relies on a centrally organized infrastructure, whereas in rural wastewater management more decentralized solutions are often applied. Centralized wastewater management systems[6] are defined as systems that collect the wastewater from all producers (such as households and industry) via sewer networks into a single treatment plant. Decentralized wastewater management systems, on the other hand, collect, treat, and

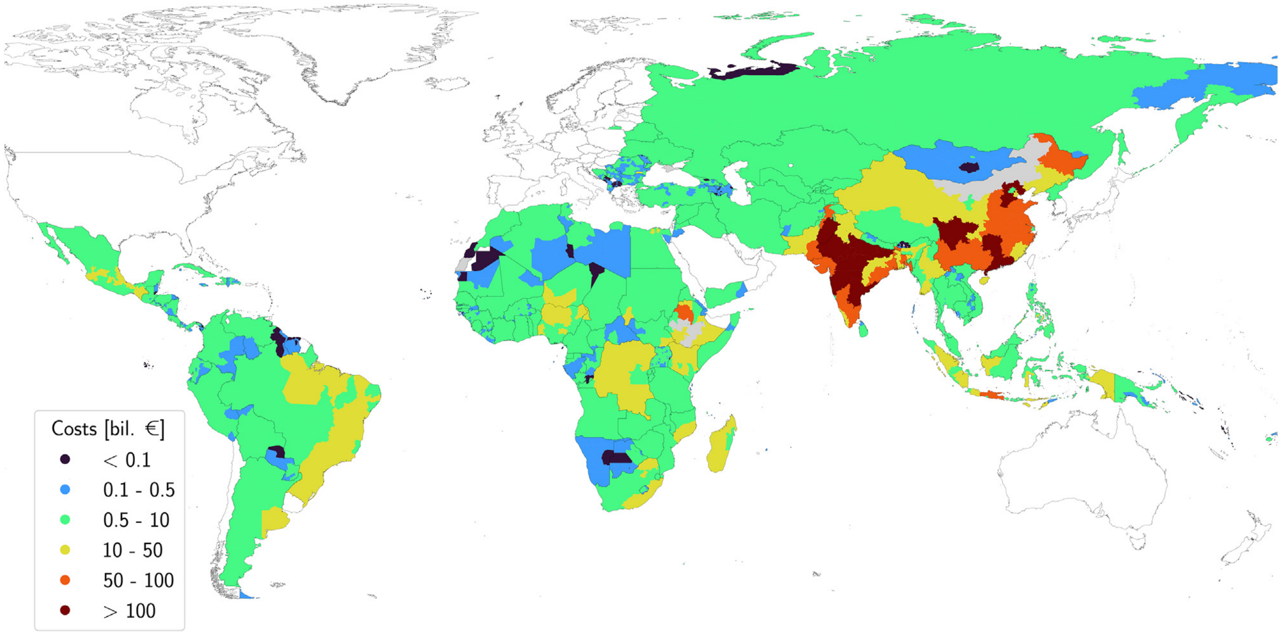

Figure 1. Maximum wastewater treatment costs without OCTOPUS

Costs are estimated for administrative division regions within 140 countries (selected based on their low coverage of basic sanitation services) and calculated as billion (10^8) euro per division. One wastewater treatment plant is assumed per settlement.

reuse or dispose the wastewater at or near its point of generation.[7] In terms of scale, the largest treatment plant is Bahr El Baqar water treatment plant in Cairo, Egypt, with a capacity to treat approximately 5.6 million cubic meters per day.[8] Decentralized wastewater treatment systems have a wide range from individual houses to several thousand "population equivalent" (PE) in smaller settlements or isolated suburbs.[9] Irrespective of central or decentral approaches, a certain daily water consumption requires a sewer-based approach. Focusing on a sewer-based approach is rooted in the concept that access to water is a human right, and according to the World Health Organization (WHO) basic needs are met by a water consumption of 50–100 L of water per person per day.[10] Such an amount of envisioned water consumption requires an appropriate wastewater treatment concept in the form of piped or sewer-based systems.

Identifying suitable and cost-effective wastewater management at a scale of relevance to SDG 6 requires planning tools that cover the relevant scales. At settlement level, planning concepts and tools for optimal wastewater management solutions focus on cost-optimized solutions[11] or scenario-based approaches.[9,11] Whereas cost-optimized solutions yield a single solution, scenario-based approaches also allow for plausible, resource-efficient, or business-as-usual water management scenarios that can then be ranked, e.g, by cost.[11] The level of planning detail provided by such tools focuses on preliminary planning stages as opposed to detailed technical and financial project planning. It is therefore important to develop transferable tools that are applicable under different local settings. Following ranked suitable solutions, detailed planning of selected scenarios is required and cannot yet be substituted.

As a starting point for assessing costs, Hutton and Varughese[12] provided estimates of the costs that are required to meet SDG 6 by 2030 at national scales for 140 countries using global assumptions and national cost data. Based on the proposed target indicators for SDG 6.1 and 6.2, costs for on-plot water supply for every household and sanitation were estimated. The countries were selected according to their low coverage of basic water, sanitation, and hygiene services[12]: mostly the world's low- and middle-income countries and a few selected high-income countries. In total, approximately 84% of the global population in 2015 was covered by the selected countries.

The global assumptions used by Hutton and Varughese[12] provide an excellent cost basis, yet do not optimize efficiency in water treatment facility costs at national scales. Whereas cost optimization approaches exist at settlement scale,[9,11,13] no planning tools at national and global scale exist that attempt to bring down the global costs required to meet SDG 6.[12]

We close this gap by providing a planning and cost optimization method, termed OCTOPUS, that can be applied at subnational scales but also include whole countries or regions. For administrative divisions such as provinces or countries, OCTOPUS provides an unprecedented tool for water master planning at the planning scale of water utility companies. Building on the idea to provide cost estimates required to realize SDG 6, our study focuses on potential cost savings by optimizing sewer-based wastewater treatment clusters. Analogous to its namesake the octopus with its central head and multiple arms, OCTOPUS estimates whether it is economically feasible to merge settlements to clusters that are serviced by the same wastewater treatment plant (WWTP). Its principle is rooted in the fact that several wastewater management costs scale according to size. Wastewater management costs (such as treatment plant investment and operation and maintenance [O&M]) follow the economy of scale, i.e., larger plants benefit from

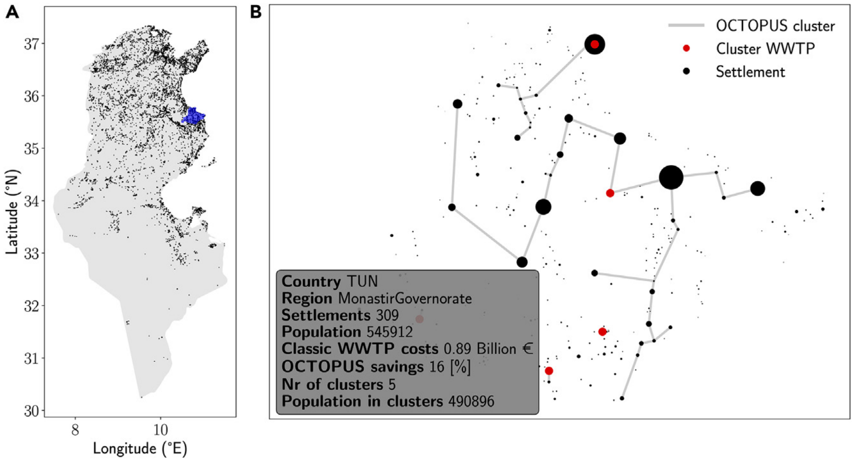

Figure 2. OCTOPUS example for Tunisia

(A) All settlements (>50 population equivalent [PE]) for Tunisia are shown; shaded in blue is the Monastir Governorate.

(B) OCTOPUS results for the Monastir Governorate, Tunisia with the identified settlement clusters connected by gray lines. Black dots represent settlements (>50 PE) and are scaled by population. Red dots represent the wastewater treatment plant location within the settlement clusters.

cost advantages when servicing more population. Thus, OCTOPUS is a treatment plant and sewer network optimizer for regions with small and medium settlements. Covering more than 4.1 million settlements in over 2,600 administrative divisions, the results show that substantial cost reductions can be achieved. For approximately one-fifth of all analyzed administrative divisions, cost savings or more than 10% compared to conventional planning can be achieved.

RESULTS

Methods summary

We estimate cost savings for 140 countries defined by Hutton and Varughese[12] at the resolution of administrative units. Whereas traditionally wastewater management planning is mostly done at the settlement scale or using very simplified assumptions at the scale of national water master plans, we identify cost savings at the scale of water utility service areas. To assess potential cost savings the OCTOPUS approach was developed, which computes whether an aggregation of wastewater treatment plants saves costs compared to individual treatment plants. Whereas such an optimization can be calculated easily for two settlements, the computation of whole regions with up to several thousand settlements becomes more complex. To this end a graph-based greedy clustering method—OCTOPUS—was developed to optimize regional wastewater networks at a near-global scale. The developed clustering methodology was fed using free globally available data sources and can be applied anywhere, also with more detailed local data. To estimate how considerable savings, compared to single settlement solutions, could be achieved by clustering settlements into larger WWTP clusters, we applied OCTOPUS at a near-global scale for 140 countries.

Global baseline and cost savings

To establish a baseline, costs for WWTP investment and O&M for a period of 20 years were calculated for all administrative regions (Figure 1) within 140 countries. The baseline costs assume a single WWTP per settlement excluding network costs within the settlements. Using the OCTOPUS approach, potential WWTP clusters have been estimated for each individual administrative region (i.e., federal states, governorates, and so forth). Figure 2A shows all settlements at country scale that are analyzed, and Figure 2B depicts the cluster results for the Monastir Governorate, Tunisia. In total, five clusters were identified that led to a cost reduction of 16% for the whole governorate. The cost reduction is in relation to the costs without any clustering approach—one WWTP per settlement—taking into account investment costs, O&M costs, and connection costs between the settlements for a duration of 20 years.

To visualize the results for the whole study region, the savings associated with the WWTP clustering are mapped in Figure 3. Although many regions in sparsely populated regions show only low saving rates below 5%, several administrative regions also depict rather high saving rates between 10% and 50%. The savings for all optimized regions show that, although approximately 20% of all analyzed region show no savings, approximately one-fifth of all regions have more than 10% savings compared to the costs without any clustering approach (Figure 4).

Subregional optimization results

The distribution of the segment lengths that connect the settlements within the identified clusters and the population of the cluster settlements give an indication of where OCTOPUS clusters can be expected. The segment length (Figure S1A) varies between 228 and 4,209 m (5th and 95th percentiles) and the cluster settlement sizes (Figure S1B) vary from 92 to 10,438 PE (5th and 95th percentiles).

Looking at the combined cluster numbers, cluster population, and total connection length of the clusters, cluster population ranges from 384 to 170,000 PE (5th and 95th percentiles) with connection lengths between 0.2 and 30 km (5th and 95th percentiles). Divided into subregions, differences in the cost savings and clusters can be seen (Figure 5). Regions with the highest cost savings—with a median above approximately 5%—are Southern, South-Eastern, and Central Asia, as well as Melanesia and Northern Africa. In terms of the amount of clusters per administrative region, Eastern Asia clearly has the highest number. However, in terms of savings this only means that other regions have fewer clusters but the cluster size, i.e., the number of connected settlements, is larger. In percentage terms, no correlation is apparent between the subregion population and the savings realized.

DISCUSSION

We utilized globally available data as well as general assumptions to estimate the potential savings in wastewater management

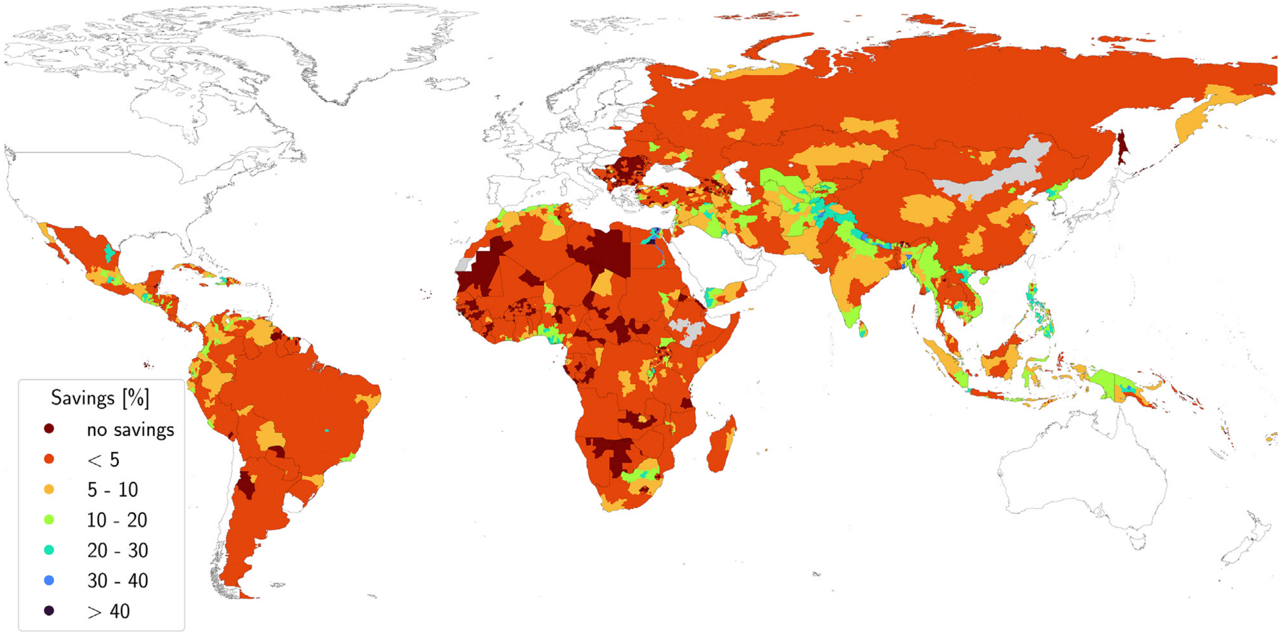

Figure 3. OCTOPUS savings (percent of maximum costs) for 140 countries
Savings are calculated per administrative division as a percentage of the maximum costs (without OCTOPUS optimization). The countries have been selected based on their low connection degree.

costs associated with clustering settlement WWTPs. Reducing the cost of wastewater management is most needed in developing and emerging regions and especially in rural settings where sanitation is still lacking.[12]

The analysis encompassed more than 4.1 million settlements in over 2,600 administrative regions of 140 countries. Next to global assumptions regarding water consumption and general treatment and sewer costs, settlement locations and population data were required. These data were taken from WorldPop[14] in gridded format and aggregated into settlements as detailed in the methodology. Although correct in terms of population data, the aggregation may result in settlement centers that cannot be directly associated with single cities or settlements in case these are connected by populated pixels. Especially large metropolitan regions that officially consist of different municipalities are thereby merged into one large urban area. At the same time it was important to utilize data that is uniformly available for all analyzed regions. While investigating specific countries or regions, of course, different data sources can be used.

The same holds true for the global assumptions whereby conservative cost estimates were taken that may not be in line with country-specific data. However, for this near-global analysis it was important to use a common basis. Different assumptions regarding sewer cost or water consumption will, of course, alter the results. One basic assumption is sewer-based wastewater management, starting with the case that each settlement has an existing treatment plant. Currently this is not true, as globally more than 50% of wastewater is estimated to be discharged untreated.[3,4] SDG indicators on targets 6.1, 6.2, and 6.3[15] do not give a clear recommendation regarding piped drinking water; however, given a water consumption of 100 liters per capita per day (lpcd),[10] sewer-based wastewater management is generally recommended simply by the fact that considerable amounts of water have to be treated and discharged that otherwise could represent an additional health risk.[16] The assumed water consumption of 100 lpcd is not meant to mimic the current water consumption in the studied regions, nor does it consider the large variability in water consumption. Instead it is based on the envisioned water consumption for SDG 6 by the UN and the WHO.[10]

Whereas the OCTOPUS clustering principle is rather basic in terms of utilizing the WWTP economy of scale and the sewer connection costs, the computation for a regional settlement network is both computation time intensive and complex. Correlations with settlement or population density do not exist, making it necessary to calculate OCTOPUS via a graph computation approach (Figure S2). Therefore, summarized results for larger regional scales (Figure 5) are used to highlight the cost saving potential in these regions but render it difficult to identify commonalities between the regions. When looking at the overall cost saving results (Figures 3 and 4), however, it can clearly be shown that substantial cost reductions are possible for approximately 20% of all analyzed regions. In addition, the cluster results give an indication of the geographic and demographic settings in which clustering can result in cost savings. Single segment lengths vary between 228 and 4,209 m, and settlement sizes within clusters range from 92 to 10,438 PE (5th and 95th percentiles).

After having successfully shown that OCTOPUS can reduce water management costs in several regions worldwide, we think that our method can be applied as a tool for water master planning. Water master planning for specific regions would require more accurate local assumptions and data. To better support

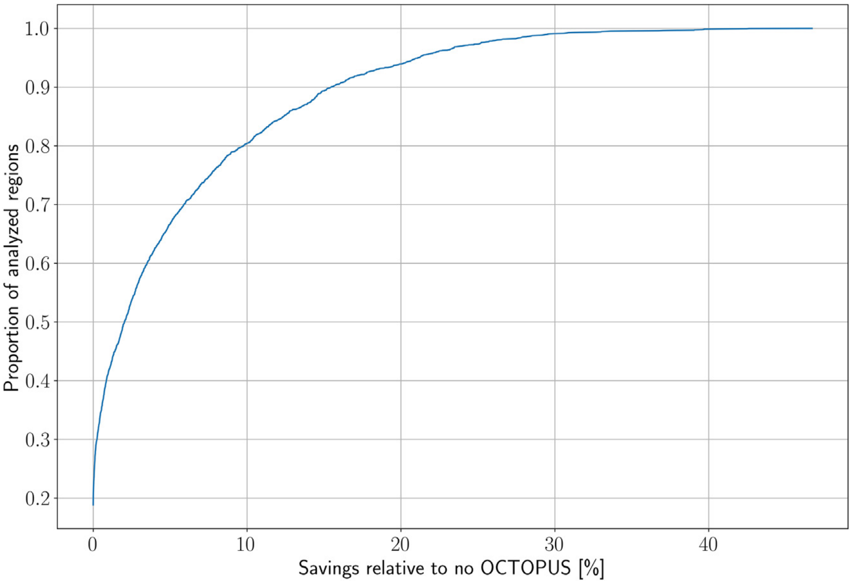

Figure 4. Distribution of OCTOPUS savings

The cumulative density function shows the distribution of savings for all analyzed administrative regions (>2,600).

the fulfillment of SDG 6, we also plan to couple the OCTOPUS approach with the ALLOWS approach.[11] The ALLOWS methodology[11] evaluates optimal wastewater management solutions within settlements and, coupled with OCTOPUS, would be applied to settlements that fall outside OCTOPUS clusters. Such detailed studies would only be feasible for specific regions with local data. At such levels further investigation into more connection options (i.e., via existing roads) or landscape obstacles would also be feasible.

Limitations

At the large scale, detailed and locally verified data sources are non-existent and would also be prone to substantial methodological differences. We therefore chose to take global data sources and make global price assumptions. When applying the OCTOPUS method at more local scale, more accurate local data and assumptions should be used. The optimization used by OCTOPUS solely focuses on reducing costs. A further constraint related to meeting SDGs is often governance.[17] For water and wastewater, governance affects the water utility companies and their ability to operate not only large central or decentral systems but also sound regulations regarding water quality and reuse. Whereas OCTOPUS does not consider strong or weak water governance, sectors in the different regions' preliminary planning tools assist and inform decision makers. Although planning tools will not solve structural governance issues, they do provide preliminary planning scenarios that, in the end, help identify the most appropriate solutions. Sound planning by OCTOPUS and tools at the settlement scale[9,11] support governance in making decisions more transparent and help save costs for detailed planning processes.

Conclusions

In view of the economic challenges associated with UN SDG 6, we have provided a planning methodology, OCTOPUS, which estimates cost savings for treatment plant (WWTP) clusters. We have applied OCTOPUS at a near-global scale covering 140 countries and for over 2,600 administrative regions. Cost estimates show that approximately 20% of all analyzed regions could save more than 10% when clustering WWTPs for several settlements. Applied at the near-global scale, of course, the results show an indication of where cost savings can be achieved. Yet the methodology itself is applicable at local scale with more realistic forcing data in terms of costs, population, and settlement data.

Globally, however, we can show that planning tools can and should be used to reduce the costs associated with SDG 6 and therefore bring us closer to meeting the goal of ensuring safe sanitation across the globe.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for data and code should be directed to and will be fulfilled by the lead contact, Jan Friesen (jan.friesen@ufz.de).

Materials availability

This study did not generate new unique materials.

Data and code availability

For population data used for the generation of global settlement boundaries, "constrained individual countries 2020 UN adjusted" datasets from WorldPop (https://www.worldpop.org/) were used.[14] Administrative divisions were taken from Natural Earth (https://www.naturalearthdata.com). The code is available at https://git.ufz.de/friesen/octopus.

OCTOPUS principle

The basic principle is to estimate the cost savings that occur when joining treatment plants of two settlements and, if economically feasible, invest the cost savings in a sewer connection. Not all costs associated with wastewater management follow the economy of scale but instead increase linearly and can therefore be ignored, as they do not benefit from higher population. Wastewater management costs that mainly benefit from the economy of scale are (1) WWTP investment costs (Figure 6A) and (2) WWTP O&M costs (Figure 6B). Using a small example of two settlements, A and B (Table 1), the following cost saving can be achieved when using a single WWTP for both instead of two separate WWTPs using Equations 1 and 2. As a status quo it is assumed that each settlement has a WWTP dimensioned toward its population.

$$WWTP_{inv} = 7117.4 * PE^{-0.347} \qquad \text{(Equation 1)}$$

$$WWTP_{om} = 480.63 * PE^{-0.198} \qquad \text{(Equation 2)}$$

where PE is population equivalent. $WWTP_{inv}$ is in € PE^{-1}. $WWTP_{om}$ is in € PE^{-1} $year^{-1}$ and has to be multiplied by PE and the number of operation years. Depending on the local costs, the $WWTP_{inv}$ and $WWTP_{om}$ can be estimated using local costs. Equations 1 and 2 are based on Tables S2 and S3, taken from MLUR.[18]

As the two settlements cannot simply be combined at no cost, such a WWTP cluster would only make sense if the savings (see Table 2) cover the

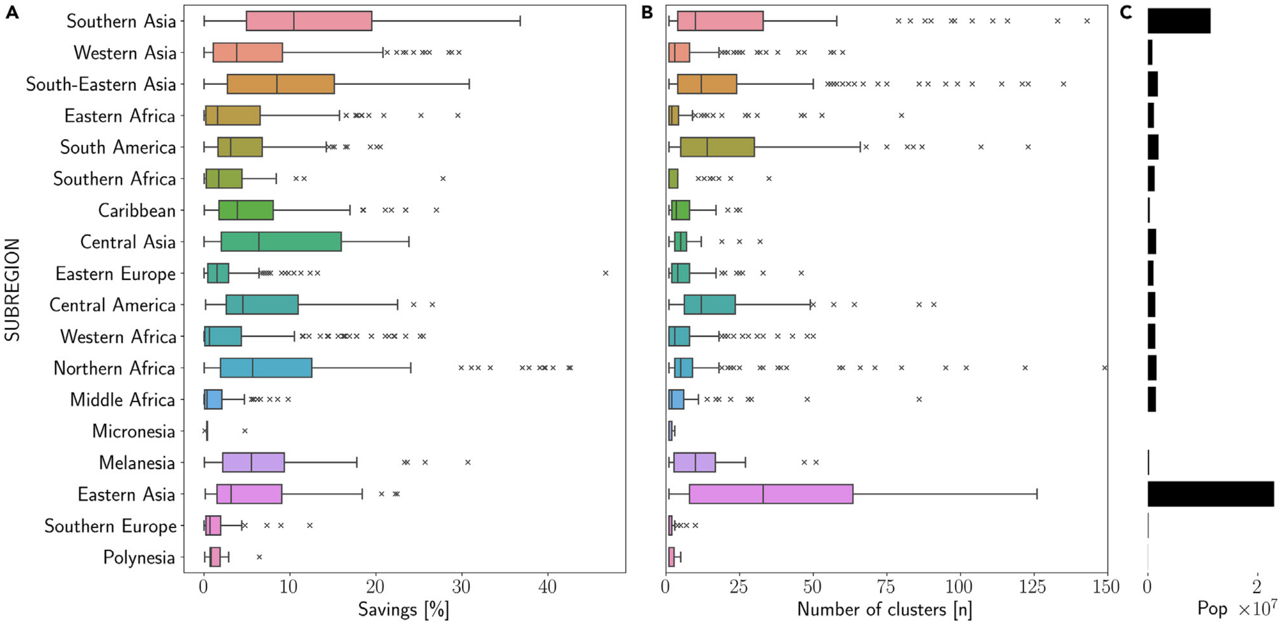

Figure 5. OCTOPUS results per subregion

Box plots of the results per subregion (see Table S1 for a country and subregion list).

(A) Savings in percent of the maximum costs without clustering.

(B) Number of OCTOPUS clusters per subregion (axis is cut at 150, single values are >800).

(C) Population per subregion.

connection costs between the two settlements. Using the distance between the two settlements, we can estimate whether the savings would cover the sewer and pump costs (Equations 3, 4, and 5) required to cover the distance.

$$P_{capacity} = (C_{PE} * PE) / 86,400 \quad \text{(Equation 3)}$$

$$P_{500} = 6,452.1 * P_{capacity}{}^{0.4357} \quad \text{(Equation 4)}$$

$$S_{total} = d * S_{construction} + P_{500} * \frac{d}{s_{pump}} \quad \text{(Equation 5)}$$

where C_{PE} is water consumption (liters per-capita^{-1} day^{-1}) (lpcd) and PE is population equivalent. $P_{capacity}$ is in L s^{-1}. P_{500} are the pump costs (€). d is the total sewer length (m), s_{pump} the pumping segment length (m), and $S_{construction}$ the sewer construction costs (€ m^{-1}). Pumps are required per 500-m sewer segment (s_{pump}).[19] As elevation differences between the settlements are ignored, a maximum pump head of 10 m per pump is taken. S_{total} is the total amount for the sewer length d including pump costs, expressed in euros. Equations 3 and 5 are based on Tables S4 and S5, taken from MLUR.[18]

For simplicity, we ignore topography. Yet, even when pumping over flat but long distances, pumping stations are required every 500 m. Table 1 shows an example assuming a water consumption of 100 lpcd[20] and 5,000 PE. In general, it can be said that by ignoring topography, the results can be seen as a lower boundary condition, i.e., settlements or clusters that cannot cover the distances based on the savings need not be considered in detailed planning. Identified clusters, however, require detailed planning that considers the actual connecting. As a result of Table 2 it would be feasible to connect settlements A and B given that the distance between the two villages is less than 4 km.

Study region

As a relevant study region for OCTOPUS, countries with a low connection degree in rural regions were selected.[12] The reasoning behind this approach is that in these regions, investment into safe sanitation is required, and the goal of this study is to estimate whether costs can be saved by aggregating WWTPs of rural settlements.

Data

As input data, global settlement boundaries and population data the "constrained individual countries 2020 UN adjusted" datasets from WorldPop (https://www.worldpop.org/) are used.[14] Administrative regions used to define the computational scale are taken from the internal administrative divisions of countries "Admin 1—States, Provinces" in Natural Earth (https://www.naturalearthdata.com). Cost data for WWTP investment, WWTP O&M, and sewer and pumping costs are based on MLUR.[18]

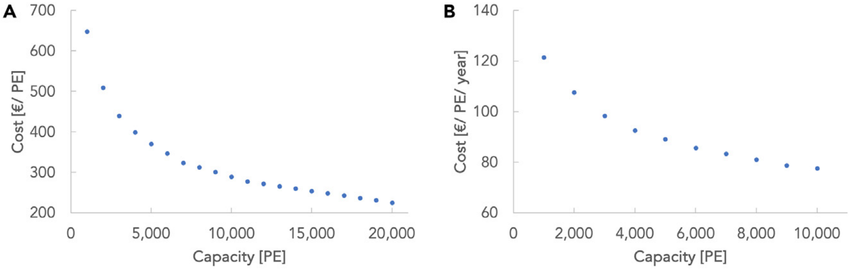

Figure 6. Economy-of-scale relationships for treatment costs

(A) Wastewater treatment plant (WWTP) investment costs in relation to capacity expressed in population equivalent (PE).

(B) WWTP operation and maintenance costs in relation to population equivalent (PE). The costs are valid for the sequencing batch reactor treatment technology. The economy-of-scale principle also holds true for other treatment technologies such as membrane bioreactor and constructed wetland.

Table 1. Cost estimates for hypothetical settlements A and B

	Units	A	B	A + B	AB	Savings
Population	PE	2,000	3,000	5,000	5,000	
WWTP	€	1,018,343	1.327,032	2,345,375	1,852,460	
O&M[a]	€	4,268,418	5.908,702	10,177,120	8,900,508	
Costs	€	5,286,761	7.235,735	12,522,495	10,752,968	1,769,527

WWTP, wastewater treatment plant; O&M, operation and maintenance; PE, population equivalent.

A + B are the combined costs of both while keeping two WWTPs, and AB are the costs when using a single WWTP for both settlements. The cost savings is the difference between scenarios A + B and AB.

[a] For 20 years of operation.

Data preprocessing

The spatially distributed population data are gridded population data constrained by built-up areas. The data were aggregated to connected pixel clusters and converted to vector data. The vector data consist of settlement polygons with total population for 2020 and corresponding coordinate centroids for each settlement. To calculate metrics such as area and distance, the data are converted to the local universal transverse Mercator (UTM) coordinate system. The local UTM projection is based on the country centroid coordinates.

Assumptions

For the connection between settlements, a direct line-of-sight connection is assumed. Elevation is not considered. Each settlement is considered to be connected to a single sewer-based WWTP. Settlement WWTPs are based on the population of the settlement, meaning that even large cities only have one single WWTP. This is not always realistic; however, such WWTPs do exist, as in the case of the Cairo megacity.[8] Further global assumptions regarding water consumption, sewer costs, O&M period, and so forth are stated in Table 3.

Spatial subsets

To estimate whether an aggregation of WWTPs exists among settlements, a reasonable spatial scale needs to be defined within which potential WWTP aggregations are estimated. As water treatment is often organized at the scale of administrative units, each country was subdivided into administrative regions (https://www.naturalearthdata.com, Admin 1—States, Provinces) at which the OCTOPUS principle was applied. Further subdivision would be beneficial in terms of computation time but is not used, as more detailed administrative boundaries are not consistently available at global level.

Network optimization method

The basic OCTOPUS principle is detailed in Figure 6 and Tables 1 and 2 using the example of two settlements. In a total of 140 countries, over 2,600 administrative regions and over 4.1 million settlements were included in the analysis. Individual regions included up to 10,000 individual settlements. To apply the OCTOPUS principle at the regional scale, we are required to not only combine two settlements but identify potential clusters among a large number of settlements (see Figure S3). This entails that clusters may grow, and, based on the new cluster population potential, connections within the whole region need to be identified.

To this end, a greedy clustering method is applied to optimize regional wastewater networks. The algorithm is based on the principles of agglomerative clustering, where new nodes are iteratively connected to existing clusters based on their dissimilarity measure (e.g., distance). However, the proposed algorithm introduces an additional step that dynamically calculates the dissimilarity measure (i.e., the cost savings of connecting a node to a cluster) with each iteration, taking into account the economy of scale within the costs of each cluster. This additional step allows for more accurate optimization of the network. The algorithm is also similar to minimal spanning tree algorithms such as the Kruskal[21] and Prim[22] algorithms, aiming to minimize the overall cost of the network. Based on the greedy clustering approach, the OCTOPUS algorithm starts with a spanning tree across all possible connections within the network (cf. Figure S3). For each connection within the network, also referred to as edge in graphs, the connection with the highest cost difference (cf. Table 2) is chosen. Based on the cost difference, the network is then allowed to grow until a negative cost difference is reached. Further, the proposed algorithm allows for multiple clusters to be formed rather than a single spanning tree; hence, it can be thought of as a minimal spanning forest algorithm. The objective function of the greedy clustering algorithm is

$$minimize \sum C_{WWTP} + C_{network} \qquad \text{(Equation 6)}$$

where C_{WWTP} is the cost of wastewater treatment plants using Equations 1 and 2 ($WWTP_{inv}$, $WWTP_{om}$), and $C_{network}$ is the connection cost between nodes in the network using Equation 5 (S_{total}).

The objective is to minimize the overall cost of the wastewater network (Equation 6) by identifying the optimal configuration of edges and clusters that minimizes the sum of the three cost components. This is achieved through iterative calculations of the cost savings for each potential connection, taking into account the economy of scale within the costs of each cluster. The final result is the optimized wastewater network that minimizes the objective function. The method was implemented using the Python programming language (Python Software Foundation, https://www.python.org). As we used a greedy clustering method, the computation time grows substantially with the number of edges in the network. Practically, this currently results in an upper limit of settlements per region that can be computed (approximately 11,000 individual

Table 2. Connection costs between two settlements

Population		5,000 PE			
Water consumption		100 lpcd			
Sewer construction costs		€400 (diameter 250, soil class 3–5, open terrain)			
Available savings		€1,769,527 (cost difference between scenarios A + B and AB)			
Distance (m)	1,000	2,000	3,000	4,000	5,000
Pump costs (€)	27,729	55,458	83,187	110,916	138,645
Sewer costs (€)	400,000	800,000	1,200,000	1,600,000	2,000,000
Connection costs (€)	427,729	855,458	1,283,187	1,710,916	2,138,645
Cost difference (€)	1,341,798	914,069	486,340	58,611	−369,118

PE, population equivalent; lpcd, liters per capita per day.

The cost difference indicates how much of the required investment would be covered by the savings of scenario AB (see Table 1).

Table 3. Global assumptions

Settings	Unit	Value
Water consumption	lpcd	100
Segment length	m	500
Sewer line costs	€ m^{-1}	1,000
O&M period	years	20
Settlement size (minimum)	PE	50

lpcd, liters per capita per day; O&M, operation and maintenance; PE, population equivalent.

settlements). Regions for which only partial cost savings could be computed are listed in Table S6.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.08.005.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.F., M.S., and M.v.A.; methodology, J.F., M.S., G.K., and M.v.A.; software, M.S. and J.F.; investigation, J.F. and M.S.; data curation, J.F. and G.K.; writing – original draft, J.F. and M.S.; writing – review & editing, J.F., M.S., G.K., and M.v.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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