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An integrated optimisation platform for sustainable resource and infrastructure planning

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A B S T R A C T

It is crucial for sustainable planning to consider broad environmental and social dimensions and systemic implications of new infrastructure to build more resilient societies, reduce poverty, improve human well-being, mitigate climate change and address other global change processes. This article presents *resilience.io*,[2] a platform to evaluate new infrastructure projects by assessing their design and effectiveness in meeting growing resource demands, simulated using Agent-Based Modelling due to socio-economic population changes. We then use Mixed-Integer Linear Programming to optimise a multi-objective function to find cost-optimal solutions, inclusive of environmental metrics such as greenhouse gas emissions. The solutions in space and time provide planning guidance for conventional and novel technology selection, changes in network topology, system costs, and can incorporate any material, waste, energy, labour or emissions flow. As an application, a use case is provided for the Water, Sanitation and Hygiene (WASH) sector for a four million people city-region in Ghana.

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Software/data availability

The *resilience.io* WASH model was built by Charalampos P. Triantafyllidis, Xiaonan Wang, Koen H. van Dam, Kamal Kuriyan and Nilay Shah from Imperial College London with data and technical support by Rembrandt Koppelaar, Zoltan Kis and Hannes Kunz from the Institute of Integrated Economic Research. The platform is designed for open-source future release by using only open-source software. A beta-version of the platform is available upon request from the authors including the data-set to reproduce the presented use case. The platform is of approximately 800MB in size on a Windows-based machine. Further details concerning the hardware/software used can be found in Table 3.

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[2] http://resilience.io/.

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1. Introduction

Several modelling techniques have been proposed to gain insights in the delivery of sustainable goals in a scientific manner. Recently, water quality performance assessment has been under the microscope (Massoudieh et al., 2017). Furthermore, in (Alhamwi et al., 2017) a GIS-based platform was introduced to facilitate storage and flexibilisation of technologies in urban areas. In (Cominola et al., 2015) the need for models that describe exogenous drivers affecting water and demand management was highlighted, to inform strategic planning and policy formation, while various platforms were also presented (DeOreo et al., 1996; Kowalski and Marshallsay, 2003; Froehlich et al., 2009; Beal et al., 2010). In (Hu et al., 2015) multi-threaded programming with Hadoop-based cloud computing was used to implement a Multi-Agent System for environmental modelling. Furthermore, in (Berglund, 2015) Agent-Based Models (ABMs) are reviewed in the context of water management planning decisions.

The benefit of planning based on advanced system models lies in the ability to rapidly carry out project evaluation within a complex city systems perspective. Such models can remove the divide between high-level master-planning and isolated low-level project planning, by enabling a link of feedback between the two, the exploration of more options and trade-offs, and enhanced visibility on positive and negative impacts in multiple-dimensions, thus lowering the risk and cost of planning. Key is not to rely on a pure techno-economic planning approach (e.g. reductionist infrastructure cost estimates), since sustainable development, social parameters and cost and benefits are inextricably bound together (White and Lee, 2009).

Concerning the presented use case application, models focusing on specific components of the water cycle are various and include agent-based water demand models with attitudes, norms, and behavioral control towards water use (Koutiva and Makropoulos, 2016), Linear Optimisation (LO) models for water supply pipe networks (Sarbu and Ostafe, 2016) and sewer pipe networks (Safavi and Geranmehr, 2016), Mixed-Integer Non-Linear Programming (MINLP) approaches for pipe network optimisation (Moeini and Afshar, 2013; Afshar et al., 2015), groundwater and rainwater storage and network MINLP (Chung et al., 2009), Mixed-Integer Linear Programming (MILP) model based water treatment technology planning including energy use estimations (Alqattan et al., 2015), and water-reuse potential estimations using a MILP architecture (Liu et al., 2015).

Complete water system models are less common, a class referred to as Integrated Urban Water Cycle Models (IUWCMs) when including all water cycle aspects, and Integrated Urban Water System Models (IUWSMs) that also integrate social, environmental, economic, and other resource flows like energy (Bach et al., 2014). Based on a literature review from 1990 to 2015 a total of fourteen existing IUWSMs were documented (Peña-Guzmán et al., 2017), although some, upon evaluation, appear to be misclassified given their too narrow usability, such as the commercial Aquacycle tool that focuses on rain and storm-water modelling (Sharma et al., 2008), or the commercial MIKE Urban software package for hydrology and flood modelling (Berggren et al., 2012). Social elements were covered in one out of fourteen models (De Haan et al., 2013), and five allowed for energy and emissions.

The two most complete IUWSM models were found to be WaterMet2 (Behzadian et al., 2014b) and Urban Water Optioneering Tool (UWOT) (Rozos and Makropoulos, 2013). WaterMet2 is an open-access difference-differential equation simulation model that integrates both natural and human water and wastewater systems inclusive of four different scales: indoor, local, catchment and city areas. These include the ability to model water demand and supply balances, pipeline fluxes, energy requirements and greenhouse gas emissions (Behzadian et al., 2014a). UWOT is an, available on request, spatially fixed fine-grained minute to hour appliance household demand model with aggregation to neighborhood and city scale. Supply is spatially solved using genetic algorithm optimisation of a pre-defined treatment plant and pipe network for water flow allocation. The platform is built in Simulink/MATLAB linked to a technology and pipeline network library database (Rozos and Makropoulos, 2013).

The main limitation of these tools is their rigidity as their goal is to analyse the performance of a user designed WASH technology-network system inclusive of any future interventions. This as opposed to starting with performance criteria as constraints on the system, including economic, environmental and social requirements and using the tool to explore urban water system design solutions that fall within the desired performance to meet future urban water cycle needs.

The gap we attempt to bridge with this platform is therefore the following: since technological innovation and planning is arguably crucial to achieve sustainable development (Anadon et al., 2016), how can technical tools assist in i) exploring planning solutions and providing the quantitative evidence on meeting the broader economic, social and environmental requirements for implementing technological investments on the ground and ii) bring *learning* and engagement of stakeholders in the full development cycle of such tools?

The first part is materialised by a systems modelling scheme; we embrace the *assemblage approach* by combining polished and well-established modelling formalisms including Agent-Based Modelling and Mathematical Programming. ABMs are becoming more and more popular in Environmental Modelling (Sun et al., 2016) and at the same time Mathematical Programming has seen enormous progress in the development of polished, consistent and accurate solvers across the latest two decades while also being one of the most widely used tools to inform transparent decision making. The intention of this approach is as analysed in (Voinov and Shugart, 2013) to allow models to exchange communication on run-time as an integrated suite which outputs meaningful results and can potentially answer an array of questions that decision makers are interested in.

The second part is effectively achieved by the open-access development cycle of the platform. A major degree of involvement by potential users and stakeholders across a variety of disciplines took place to elaborate on the optimal design, implementation and usefulness of the platform while not over-complicating the models. By conducting a series of communication exchanges with local experts in Ghana from various institutions (e.g. Ghana Water Company, University of Ghana, etc.), and delivery of an early version for testing, we tried to shape the platform to best serve the user needs to assess policy implications so as to reach sustainability targets in the most realistic manner.

This article is organised as follows: in section 2 we present the modelling techniques built-in to the platform. In section 3 we describe the link between the models and the input data, and the associated mechanisms as well as the major implementation details. Section 4 demonstrates a series of questions that can be potentially answered by using *resilience.io*. Section 5 presents the WASH sector use case as a first application as well as the context upon which the analysis was built. Results follow in section 6. A comparison of the developed platform with the WaterMet2 and UWOT models, as well as limitations and advantages of our approach are given in the discussion section 7. We give our conclusions in section 8. Finally, the data-set for the MILP optimisation and examples of automated plots from the platform can be found in the Appendix.

2. Methods

As a novel implementation of the concept to combine technical planning with socio-economic evaluation we built a set of models of infrastructure systems at a fine-grain spatial and temporal scale within a socio-economic context. We start with human behavior and decisions, by first defining population variability (Bentsi-Enchill et al., 2010; Ghana Statistical Service, 2010) and simulating how it affects daily activities and location, from which needs emerge (for instance water demand) as well as environmental impacts (generation of waste-water). We therefore apply predictive (*inductive*) modelling in the sense that we used predefined sets of variables (population characteristics), and their projected change into the future, that are coupled with demand requirements. We then connect these demands to a supply-flow optimisation model which links technology inputs and outputs in any dimension (energy, materials, emissions, wastes, labour) to find multi-objective solutions to technology investment and operation, including cost and sustainability criteria.

We follow the meticulous review in (Hamilton et al., 2015) concerning the dimensions upon which software based tools which facilitate Integrated Environmental Modelling (IEM) should be designed and developed. We also employ data-sets as the intermediate tool between modular modelling methodologies presented herein, so as to follow the discipline presented in (Laniak et al., 2013). To this respect we treat the whole data-set package as a scenario which not only defines the model output, but enables to present different renditions based on user-defined actions, without altering the model structure, and to establish a link to the next scenario run by outputting data-sets which can then be used as inputs.

The description of our framework is following the sequentially implemented mechanisms:

1. Demographics calculation, as the fingerprint of population and social-economic conditions;
2. Agent-Based Modelling (ABM) as the simulation module to estimate demands;
3. Resource-Technology Network Modelling (RTN), as the decision support module to meet demands from the supply side.

A series of different software tools (following the flow of design-execution) were used into the making of this platform:

- YAML (YAML, 2017) human friendly data serialisation language for input-output of parameter data,
- Java 8 (Java, 2016) to code the Demographics, ABM and RTN modules,
- GLPK (GLPK, 2016) as the Mixed-Integer Linear Programming (MILP) open source optimisation solver and
- R (R-project, 2016) for post processing and visualising outputs for ABM and RTN.

All of the required packages and libraries used are bundled within the suite itself. There is no need for extra installations from the user side to run the platform. We will now analyse each of the modelling components separately.

2.1. Demographics calculation

For the specified application sector, the following characteristics articulate the agent variability: district, gender, age group, work force, income, access to drinking and non-drinking water infrastructure, rationing policy and toilet type. The combination of these characteristics forms a unique combination which we call an Agent Combination Archetype (ACA). We also define a simpler set of company agents based on their type and number in each sector in relation to water usage. We included four attributes for this module: district, sector, water use on business basis (m^3/day). The changes in demographics are calculated on the basis of an initial master table with all 3,700 ACAs compiled for the baseline year using several databases. The number of people and households belonging to each ACA changes over time based on proportionally transposing demographic rates Δ to each ACA. As such a unique master-table for each future year is generated that can be used as an input for the ABM demand component. The influence of urban dynamics such as population migration within the modelled area and migration from/to the outside world was not specifically modelled but included on an exogenous scenario basis. Future extension of the *resilience.io* model to endogenously include this feature or linkages to existing models of urban dynamics (Galan et al., 2009) is envisioned. The rate parameter values are logged into a structured YAML file that is read by the demographics module.

The parameters and variables included in the demographics update of the master table are as follows, including naming in light gray colour on the right side, as for the rest of our model outline:

P : *Population*
$\Delta(A)$: *Aging Rate*
D : *Deaths*
B : *Births*
I : *Immigration*
E : *Emigration*
M : *Migration*
EM : *Employment*
UE : *Unemployment*
ER : *Employment Ratio*
LI, MI, HI : *low-medium-high Income*
LM : *LI to MI % change*
MH : *MI to HI % change*
CC : *Companies count*

The first update to the socio-demographic master-table is carried out as follows to update for aging, birth, death and migration:

$$
\begin{aligned}
&P(t) = P(t) \cdot (1 + \Delta(A)) \\
&D(t) = P(t) \cdot (1 - \Delta(D)) \\
&B(t) = P(t) \cdot (1 + \Delta(D)) \\
&I(t) = P(t) \cdot (1 + \Delta(I)) \\
&E(t) = P(t) \cdot (1 - \Delta(E)) \\
&P(t+1) = P(t) + B(t) - D(t) + M(t)
\end{aligned}
$$

Next socio-economic changes in employment are calculated to update the master table based on an assumed decline in unemployment. The implementation uses a logistics curve as a simplified approximation of change in a growing economy, such that the speed of change can easily be adjusted and a maximum unemployment rate is maintained as:

$$\Delta(EM)(t+1) = 0.05 \cdot ER(t)\left(1 - \frac{ER(t)}{\max(EM)}\right)$$

$$EM(t+1) = EM(t) \cdot \Delta(EM)(t+1)$$

$$\Delta(UE)(t+1) = 0.05 \cdot (1 - ER(t)) \cdot \left(1 - \left(1 - \frac{ER(t)}{\max(E)}\right)\right)$$

$$UE(t+1) = UE(t+1) \cdot \Delta(UE)(t+1)$$

Subsequently, a set of socio-economic calculations are made to update income level changes in the master table. The calculation takes into account low, medium, and high income levels per population category, as initiated from income estimates, which were inferred from wage estimates and their distribution. The calculation allows for either downward or upward migration from/to income categories, signalling income increase or decrease depending on the required simulation. The calculation is carried out as follows:

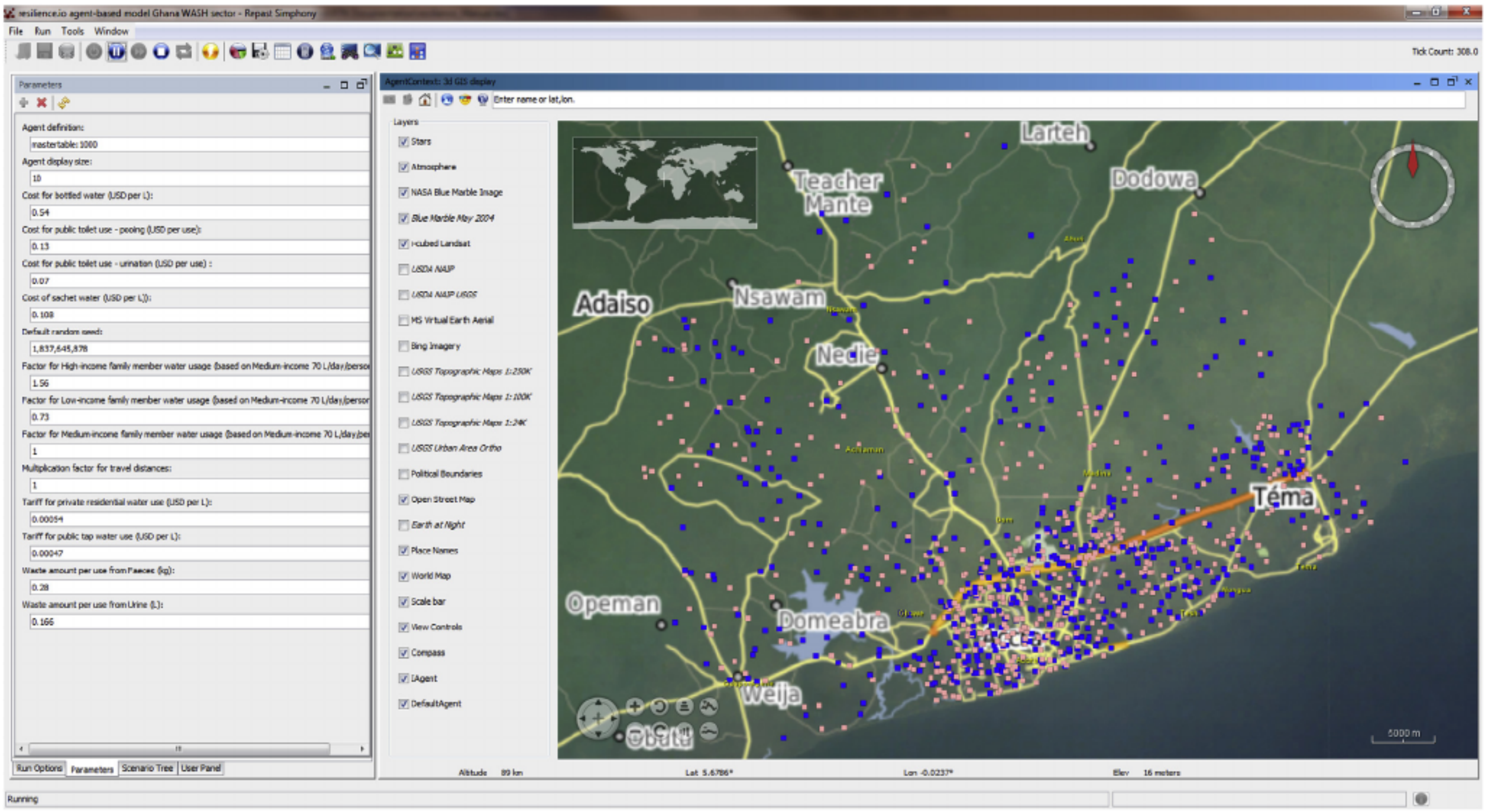
$$LI(t+1) = LI(t) - MI(t) \cdot LM$$
$$MI(t+1) = MI(t) + MI(t) \cdot LM - MI(t) \cdot MH$$
$$HI(t+1) = HI(t) + MI(t) \cdot MH$$

The number of households related to the population were proportionally estimated using a fixed ratio. Finally, the adjustment for the companies in relation to employment change in a proportional manner is carried out as:

$$CC(t+1) = CC(t) \cdot (1 + \Delta(EM))$$

2.2. Agent-Based Modelling

For the Agent-Based Model (Bonabeau, 2002) we used Java-based Repast Simphony (Repast Simphony, 2016), which is a free Agent-Based simulation toolkit specifically designed for the systematic study of complex system behaviors. A description of the ABM in the Overview, Design concepts, Detail (ODD) protocol format (Grimm et al., 2010) is given in Table 2. First, a *synthetic population* is generated which represents the actual population of the city, visually shown in Fig. 1. Some details about the agents and their attributes are shown in Table 1. A population master table, which contains over 3700 possible Agent Combination Archetypes (ACAs), approximately 250 per district based on nine characteristic combinations as per Table 1, is used by the ABM to draw a random sample of agents to simulate, using the number of people represented by an ACA as the probability. The result of this process is an agent population with a distribution of agent properties that closely resembles the actual population, as represented ACAs cover 90% of real population variation. The final simulation outcome based on individual agents is scaled up by their proportion to obtain results for the whole population of Greater Accra Metropolitan Area (GAMA). In this agent generation process each agent is allocated to a home district, but in addition the model chooses a work location if applicable, depending on the work force status. This work location is typically near home for people on low income (approximately $\leq$ 2 USD per day), but can be in other parts of the city region for those with a higher income able to afford public or private vehicle transport. The steps to form a demand profile for each district in the study include:



Agent definition:
mastertable: 1000
Agent display size:
10
Cost for bottled water (USD per L):
0.54
Cost for public toilet use - pooing (USD per use):
0.13
Cost for public toilet use - urination (USD per use) :
0.07
Cost of sachet water (USD per L):
0.108
Default random seed:
1,837,645,878
Factor for High-income family member water usage (based on Medium-income 70 L/day/perso
1.56
Factor for Low-income family member water usage (based on Medium-income 70 L/day/person
0.73
Factor for Medium-income family member water usage (based on Medium-income 70 L/day/pe
1
Multiplication factor for travel distances:
1
Tariff for private residential water use (USD per L):
0.00054
Tariff for public tap water use (USD per L):
0.00047
Waste amount per use from Faeces (kg):
0.28
Waste amount per use from Urine (L):
0.166

Layers
☑ Stars
☑ Atmosphere
☑ NASA Blue Marble Image
☑ Blue Marble May 2004
☑ i-cubed Landsat
☐ USDA NAIP
☐ USDA NAIP USGS
☐ MS Virtual Earth Aerial
☐ Bing Imagery
☐ USGS Topographic Maps 1:250K
☐ USGS Topographic Maps 1:100K
☐ USGS Topographic Maps 1:24K
☐ USGS Urban Area Ortho
☐ Political Boundaries
☑ Open Street Map
☐ Earth at Night
☑ Place Names
☑ World Map
☑ Scale bar
☑ View Controls
☑ Compass
☑ IAgent
☑ DefaultAgent

Fig. 1. ABM map and agents Graphical User Interface (GUI). The gender is depicted by different colors and the mobility of the agents is also shown real-time. The ABM is taking place on the real map of the city-region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Agent properties and possible values.

Characteristics	Values
District	15 Metropolitan, Municipal and District Assembles (MMDA)
Gender	Female/Male
Age group	0-14/15+
Income level	High/Medium/Low income family
Work force status	Employed/Not active or unemployed
Drinking water access	Private pipe access/Sachet water/Public tap or Stand pipe/ Bottled water/Protected decentralised source/Tanker supply or Vendor provided/Unprotected decentralised source
Non-drinking water access	Private pipe access/Public tap or Stand pipe/Protected decentralised source/Tanker supply or Vendor provided/ Unprotected decentralised source
Rationing	Yes/No water supply rationing impacts
Toilet Access	Public Toilet/W.C./Kumasi VIP/No facilities etc.

1. Estimate water **use behavior** and amount for each category of Agent Combination Archetypes on discrete time intervals (e.g. typically daily or hourly), expressed as $D_i(\tau)$, $\tau \in [n\Delta, (n+1)\Delta)$, where $D_i(\tau)$ is the water demand of the i-th archetype at discrete time interval τ, and Δ represents each time interval that composes a full day.
2. Select the proper **regression functions** using the data to obtain a time-dependent formula that can describe at a fine-grained 5 min interval the tendency and value range of water demand, taking into account ACA characteristics, such as a polynomial or sum of sine regression models, for example $D_i(t) = \sum_{j=1}^{N} a(j) \cdot \sin(b(j) + c(j))$. The choice of regression function depends on the water demand pattern that is simulated whereas in principle non-linear functions are applicable. A polynomial function was tested as having the best fit to the water demand data ($R \sim 0.98$).
3. Run the agent **activity** models that links location to water demands using the regression functions to obtain a five minute interval location specific water demand for each ACA.
4. Write *.csv* output files containing the temporal and spatial specific demand data **scaled up** from the sample simulated agents to the entire population.
5. **Visualise** the demand data (see Fig. 5) and input the *.csv* dataset to the **optimisation** model (RTN) for further planning and operational purpose.

We initially assumed a fixed 80% of total water demand to be converted to waste-water to be treated based on standard loss assumptions (Tchobanoglous et al., 2014). This is to simply link the amount of waste-water to total water usage. However, the user can define a different percentage or absolute values per district for the waste-water generated inside the YAML data file. The amount of waste-water can also be obtained from ABM based on agents' activities, if a more specific study is desired.

2.3. Resource - Technology Network Modelling

To enable the open-source and open-access character of the platform, the optimisation module should be able to basically reproduce the functionality of a modelling language (such as the General Algebraic Modelling System (GAMS)), with as possible minimum loss of generality. This means that the Java code should be capable of building the model based on the inputs from scratch and pass the formulated optimisation problem to the solver as any modelling language would do. Furthermore, in order to cross-validate consistency and check the integrity of the generated models from the RTN component, we compared the equivalent model written in GAMS and performed element-to-element comparison of the compiled *.mps* files respectively, in MATLAB.

The Resource - Technology Network (RTN) is a Mixed-Integer Linear Programming (MILP) model (Bertsimas and Tsitsiklis, 1997), derived from a retrofit version of the original Technologies and Urban Networks (TURN) model (Kierstead and Shah,

Table 2
ODD protocol description of the ABM.

Elements of ODD protocol	Description
Purpose	Model water consumption
Entities	Individuals/citizens
State variables	District, age, gender, work force, income rank and access to infrastructure
Scales	Spatial (location of agent) and temporal (5 min interval update of activities)
Process overview and scheduling	1. Agent Factory defines synthetic population 2. Characteristic's variation leads to demands for water 3. Factors to fit consumption levels per person can be parametrised
Design concepts	1. Synthetic population from a pre-processed master table of the actual population with socio-economic variants 2. The demand for water is estimated based on agent's activities defined in the context manager 3. Output is visualised and linked to RTN
Initialisation	Agent factory defined by the master tables and population density per zone, define initial state of agents
Input data	Probability model describes agent's activities as $AP_a \triangleq \{(ACT_n, MT_n, SD_n, PS_n)\}_a, \forall\ n \in N$: - Activity pattern AP_a for agent a - Each specific activity n ACT_n - Activity occurs at the mean starting time MT_n - Standard time deviation as SD_n - Probability of starting the activity as PS_n
Submodels	Polynomial or sum of sine regression models are adopted to estimate patterns within the desired goodness-of-fit so as to analyse time-varying consumption of water

2013). It calculates the flows and inter-conversion of resources given specific technological infrastructure via a spatial and temporal approach. The run results are suggested investments in technologies or transport network expansion following a cost minimisation approach so as to meet the projected water and sanitation demands generated from the ABM component. A distinct degree of flexibility is given throughout the whole model including the capability to introduce new technologies and any input-output flow vector (materials, wastes, energy, labour and emissions), allowing imports and exports, restricting flows and defining upper bounds, investment costs and leaks of transport links as well as changing maps of the initial transport network and setting where cell to cell flow expansion is admissible/feasible. Also the optimisation uses a flexible weighted multi-objective that can in the current version be tailored to incorporate economic (financial cost), environmental (waste and emissions) and social aspects (labour). In the use case implementation a joint financial cost and greenhouse gas emission minimisation objective was used. A more detailed discussion about the way the user can craft input data to answer different questions is also given in section 4. The following is the description of the RTN model we used:

Indices/Sets

$flow(r)$:	*all flow-able resources*
$flow\_1(r)$:	*resources which can flow in potable water pipes*
$flow\_2(r)$:	*resources which can flow in waste-water pipes.*
$i, i'(alias)$:	*zone/cell/district/ MMDA*
j :	*type of technological infrastructure*
m :	*metrics as* $CAPEX\text{-}OPEX\text{-}CO_2$
r :	*type of resource (material/energy)*
t :	*minor time period, as fractions of a single day*
tm :	*major time period, as years*

Parameters

$CAP(j)$:	*nameplate capacity of* j
$CF(j)$:	*capacity factor of* j
$CLEN$:	*scaling factor to represent distance in km*
$dist(i, i')$:	*distance from* i *to* i'
lp :	*percentage of leaks* $\in (0, 1)$
$MU(j, r)$:	*rate of* r *prod/consumption per unit of* j
$OBJWT$:	*metric-related weights for the objective function*
PHI :	*hours assigned for a year, at each minor time period* t
$Qmax$:	*maximum flow of resources in all pipes*
$VI(r, m)$:	*import value value of* r/m
$VIJA(j, m)$:	*technology* j*/metric* m *investment coefficient*
$VPJ(j, m)$:	*technology* j*/metric* m *process coefficient*
$VQ(flow, m)$:	*flow value of* r/m
$VY(nt, m)$:	*value per meter of network of* r/m
$X(i)$:	x *co-ordinate of* i
$Y(i)$:	y *co-ordinate of* i

Positive Variables

$IM_{(r,i,t,tm)}$:	*import of resource* r *in cell* i *period* t *major period* tm
$Leak_{(r,i,i',t,tm)}$:	*leaks in flow of* r *from* i *to* i' *in* t *and* tm
$P_{(j,i,t,tm)}$:	*production rate of tech* j *in* i *in minor period* t *and major period* tm
$Q_{(r,i,i',t,tm)}$:	*flow of* r *from* i *to* i' *in* t *and* tm
$RS_{(r,i,t,tm)}$:	*net surplus of resource* r *in cell* i *in minor period* t *and major period* tm
$VM(m, tm)$:	*total value of metric* m *in major period* tm
Z :	*the objective function*

Integer Variables

$INV_{(j,i,tm)}$:	*number of units of* j *invested at* i *in* tm
$N_{(j,i,tm)}$:	*number of tech* j *in cell* i *in* tm

Binary Variables

$Y1_{flow\_1,i,i',tm}$:	*If the potable water network is built or not*
$Y2_{flow\_2,i,i',tm}$:	*If the waste-water network is built or not*

Formulas:

$$dist_{(i,i')} = \left(\sqrt{(X_i - X_{i'})^2 + (Y_i - Y_{i'})^2}\right) \cdot CLEN \quad \textit{distance between cells}$$

A set of constraints is defined to upper bound production rates, the allocation of the units of technologies in relation to investments as well as to simulate how the resource balance is calculated as a result of production-imports and bidirectional flows and leaks on the transport network so as to satisfy demands in potable water. The weighted sum of metrics is the objective function to be minimised. Key Performance Indicators (KPIs) serve as the metrics here, as per the use case OPEX, CAPEX and emissions of GHG in CO_2.

Constraints:

$$N_{(j,i,tm)} = N_{(j,i,tm-1)} + INV_{(j,i,tm)}, \quad \forall j, i, tm \quad \textit{Technology balance}$$

$$P_{(j,i,t,tm)} \le N_{(j,i,tm)} \cdot CF_{(j)} \cdot CAP_{(j)} \quad \forall j, i, t, tm \quad \textit{Production}$$

$$Leak_{(r,i,i',t,tm)} = lp \cdot Q_{(r,i,i',t,tm)} \quad \forall r, i, i', t, tm \quad \textit{Leaks}$$

$$Q_{(r,i,i',t,tm)} - \tfrac{Q_{max}}{(PHI_{(t)}/8760)} \cdot Y1_{(r,i,i',tm)} \le 0 \quad \forall r, i, i', t, tm \quad \textit{Flow constraints, potable water}$$

$$Q_{(r,i,i',t,tm)} - \tfrac{Q_{max}}{(PHI_{(t)}/8760)} \cdot Y2_{(r,i,i',tm)} \le 0 \quad \forall r, i, i', t, tm \quad \textit{Flow constraints, waste-water}$$

$$\begin{aligned} D_{(r,i,t,tm)} = {} & \sum_{j} MU_{(j,r)} \cdot P_{(j,i,t,tm)} \quad \textit{Mass Balance} \\ & + (1 - lp) \sum_{i'} Q_{(r,i',i,t,tm)} \\ & - (1 - lp) \sum_{i'} Q_{(r,i,i',t,tm)} \\ & - \sum_{i'} Leak_{(r,i,i',t,tm)} \\ & + IM_{(r,i,t,tm)}, \quad \forall r, i, t, tm \end{aligned}$$

$$\begin{aligned} VM_{(m,tm)} = {} & \sum_{j,i} VIJ_{(j,i,m)} \cdot INV_{(j,i,tm)} \quad \textit{metrics calculation} \\ & + \sum_{j,i,t} VPJ_{(j,m)} \cdot P_{(j,i,t,tm)} \\ & + \sum_{r,i,i',t} VQ_{(r,m)} dist_{(i,i')} \cdot Q_{(r,i,i',t,tm)} \\ & + \sum_{r,i,i'} VY_{(PW,m)} dist_{(i,i')} \cdot Y1_{(r,i,i',tm)} \\ & + \sum_{r,i,i'} VY_{(WW,m)} dist_{(i,i')} \cdot Y2_{(r,i,i',tm)} \\ & + \sum_{r,i,t} VI_{(r,m)} \cdot IM_{(r,i,t,tm)}, \quad \forall m, tm \end{aligned}$$

Objective function:

$$Z = \sum_{m,tm} OBJWT_{(m,tm)} \cdot VM_{(m,tm)} \quad \textit{Objective function.}$$

In terms of Linear Programming (LP), we will show how the model represents an MILP problem. Consider the following primal linear programming problem in standard format:

$$\begin{aligned} &\textit{minimise} && c^T x \\ &\textit{subject to} && Ax = b, \\ & && x \ge 0 \end{aligned}$$

where x are the decision variables, $A \in R^{m \times n}$, $b \in R^m$, $c,\ x \in R^n$, T denotes transposition, and $rank(A) = m$, $1 \le m \le n$. It is now easy to link the model components with the strict mathematical form of the MILP problem. Coefficient matrix A is the set of constraints (row-by-row) as production limitations, flow constraints, mass balance etc., c is the objective function (weighted sum of metrics) and b is the right-hand side (*RHS*) which reflects to the specific resource demands in this case. Variable vector x is the combined sets of variables (column-by-column) in the problem (P, N, Q, INV, RS, $Leaks$, $Y1$, $Y2$, IM, VM). Positivity of some variables is required as shown, N, INV need to be integers and $Y1$, $Y2$ are binary variables, thus converting the original LP to MILP.

This set of variables is to be determined in such a way that all constraints are satisfied and at the same time the objective function is optimised. This includes the production values P, the number of units N for each different type of technology as well as the investments, the production surplus RS in each cell and the flow amount Q from/to each cell for each resource being able to flow. Imports IM define resource inputs without the need of implemented technologies to produce them, and the weighted sum of metrics is forming the objective function as a dot product of CAPEX, OPEX and CO_2 with their respective weights. For the transport network topology and the associated flow constraints we use binary variables which stand for whether the network is already built (1) or not (0) between all the possible combinations of the cells. The feasibility of constructing a pipe or technology in a cell is also set based on a binary variable approach, to rule out impossible placements (e.g. seawater desalination plants inland).

3. Data - implementation details

One of the most important structures in the platform is the demand for specific resources (such as potable clean water) which is generated by the ABM module. The demand is a function of resources, cells, and minor and major periods of time. This enables flexibility in customising demand values differently within the same day over a year's length (for instance also to simulate seasonal variation). Besides having the ability to read the ABM demands using the generated *.csv* file, the user can also run the demands as manually defined exogenous inputs, by defining them inside a structured YAML file. This is to allow modular execution of the RTN component, without the need to execute the ABM module first.

A full list of components inside the YAML input data file are given in Table 4. A YAML object is linked with a Java class object, in the sense that all of the YAML components are actually attributes of a single Java class instance; in this way maintenance and upgrade of the data-input of this platform is straightforward, clean and easy to implement. A scheme showing how single read/output YAML commands can access all of the scenario attributes at once for a single run is shown in Fig. 3. Additionally, *NO.yml* is a YAML file generated by the platform, which contains the optimal infrastructure with investments so it can be used as a pre-allocation status for a future run. Finally, a series of sanity checks are performed upon reading the YAML data file to ensure consistency of the expected sizes and content of the components.

Some fundamental technical attributes of the technological infrastructure are required in the YAML data file. For instance, capacity factors and nameplate capacities play a role in defining the maximum production rates of the technological units. A series of tables are used to summarise conversion relationships between resources and technologies, efficiency coefficients and flow-import-investments costs. We also use a 2-D coordinate system for the centroids of the cells to calculate their relational distance in kilometers. In addition the extra component in the YAML file, *coords* serves as a way of changing the visual representation - geolocalisation of the cells, without affecting the calculations of resource flow cost which is handled by the XC, YC attributes. Besides the coordinate requirement for visual representation, this is to additionally scale the operational cost of flows or pipe expansions based on the distance of the corresponding flow path.

The link between the ABM generated demands and the MILP optimisation problem is clearly plugged in at the Right-Hand Side (RHS) of the MILP problem, and specifically in the mass-balance constraint rows. As the ABM finishes calculating projected demands, the results are stored in a *.csv* file which can then be (sequentially) read to initialise demands for the RTN component. The YAML file is read to provide parameter values for the MILP model, which are logged inside Java via the GLPK interface when the MILP problem is built and passed to the optimisation solver to acquire the optimal solution (if such exists). Although the model is feasible in nature (investments can be used to further extend production output so as to meet demands) some modifications can affect feasibility; these include bounding the investments in specific cells in combination with the absence (and limited expansion availability defined by the user) of pipe network connectivity, which if not restricted would allow for surplus production to flow so as to meet demands.

The platform has been designed and optimised (using memory pre-allocation, sparse-matrix handling with the UJMP Java class package (UJMP, 2016) being essential to allow scaling of the model for very large dimensions using small sizes of RAM, fine tuning of the solver for the specific formulation etc.) for use with medium-specifications laptops, therefore it is lightweight in the required computational power, and produces results within very reasonable cpu-time for single scenario runs (usually a few minutes or even less, depending on the complexity of the problem). The whole platform consists of the three modules (demographics, ABM and RTN), the required Java Run-time Environment (JRE) and R programming language packages, all bridged together. Upon execution it outputs automated plots inside categorised (investments, network, flows, infrastructure etc.) *.pdf* files. The Graphical User Interface (GUI) shown at the initial execution of the platform is shown in Fig. 2. The ability to solve the formulated MILP optimisation problem with commercial solvers (such as CPLEX) is also possible as the platform exports the *.mps* problem format via the GLPK interface before applying the GLPK MILP solver. The overall flow of the implementation is shown in Fig. 4.

The computational environment we used for the use case is shown in Table 3. The total run time for all scenarios was around 23 min (1400 s). Most of the MILPs formulated under the RTN model are extremely sparse. For instance for the 2030 SDG's scenario the MILP is of $2,996 \times 4,068$ size (rows × columns, or constraints × variables) and 12,700 non-zeros (the number of nonzero entries in the coefficient matrix A of the MILP problem) which accounts for $\left(\frac{12,700}{2,996\cdot 4,068}\right) = 0.1‰$ density. This enables wide applicability and accelerated converge with the latest Mixed-Integer Linear Programming solvers at our disposal.

Table 3
The environment used for the use case computational runs of the *resilience.io* platform.

CPU:	Intel®Core™i7-2630QM 2.0 GHz Q1 ′11
RAM Size:	4 GB DDR3 1333 MHz
Cache size:	6 MB
R version:	3.2.5
YAML (Snake flavor)	1.15
Java version:	1.8.0.92
GLPK version:	4.57
UJMP version:	0.3.0
Operating System:	Windows 10 × 64

4. Functionality

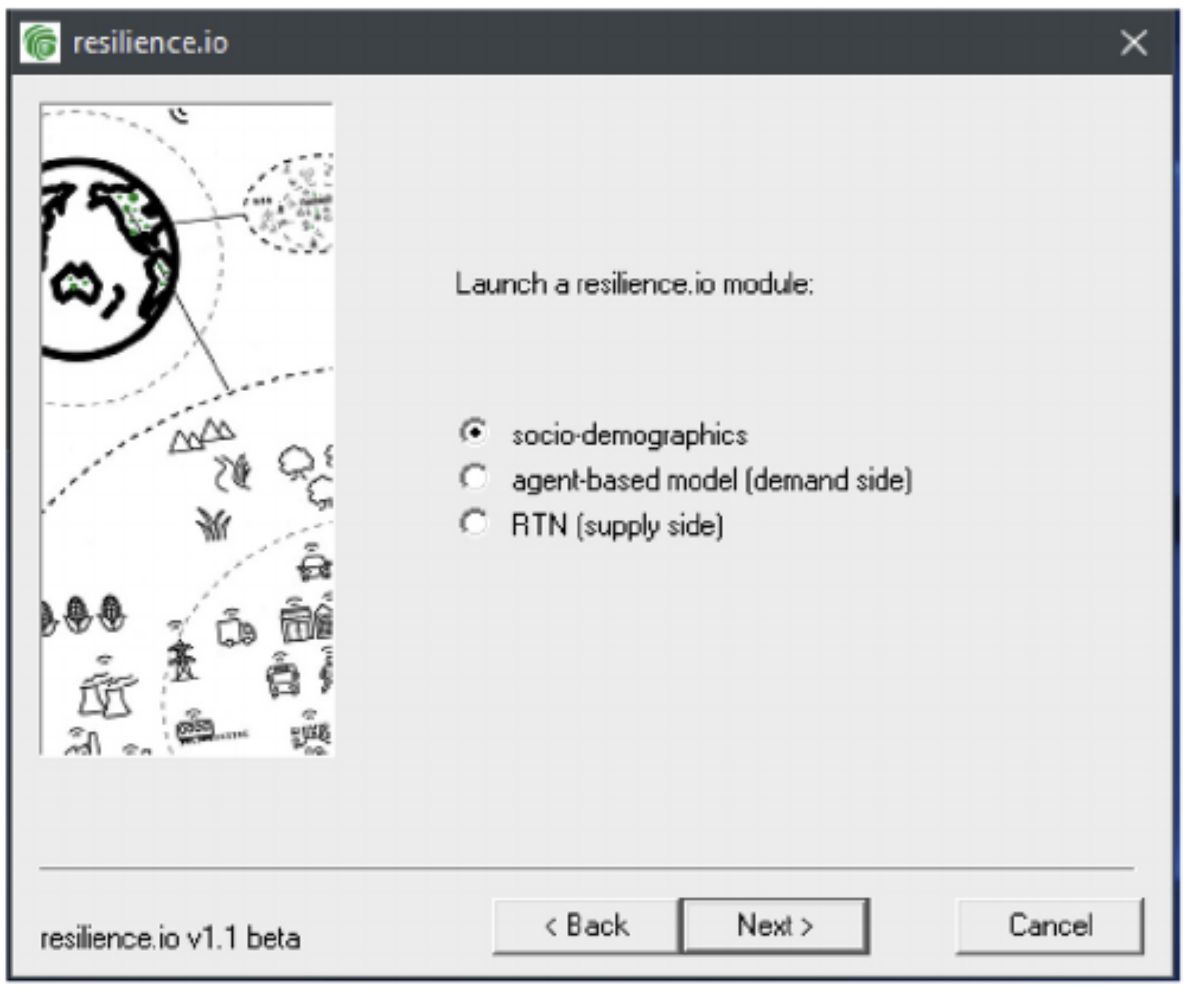
A series of specific questions can be answered via the optimisation module; what kind of investments do we need to meet growing demands and sustainable development targets? What capacity, of which type and where to place the required technologies? Which changes to the resource flows (transport network) between cells (e.g. city districts) are needed? What is the proposed

Table 4
This table describes all the components inside a YAML input data file for initialising the RTN module.

NAME	STRUCTURE	TYPE	SIZE	ROLE
CAP	Vector	String	$1 \times j$	Nameplate capacity of each technology
CF	Vector	Double	$1 \times j$	Capacity factor of each technology
imp_r	Vector	String	$1 \times imp\_r$	Resources which can be imported
impcells	Vector	String	$1 \times impcells$	Cells that are capable to import resources
flowresources	Vector	String	$1 \times flowresources$	Resources which are allowed to flow
pipes	Vector	String	2×1	The pipe types (e.g. potable/waste)
m	Vector	String	$1 \times m$	The metrics (KPIs)
CLEN	Scalar	Double	unary	Scaling factor of distance to km
MU	Matrix	Double	$j \times r$	Conversion efficiency of tech/resources
N_alloc_Matrix	Matrix	Double	$i \times j$	Pre-allocated infrastructure matrix
ODS	Matrix	Double	$i \times 2$	Overall demands for potable/waste water per cell per year
PHI	Vector	Double	$1 \times t$	Number of hours of production per minor period
VI	Matrix	Double	$imp\_r \times m$	Import cost of resources per unit
VIJA	Matrix	Double	$j \times m$	CAPEX of each technology
VPJ	Matrix	Double	$j \times m$	Efficiency factors for production
VQ	Matrix	Double	$flowresources \times m$	Flow operational cost of each resource
VY	Matrix	Double	$pipes \times m$	CAPEX to build a pipe for each type of network
XC	Vector	Double	$i \times 1$	X-coordinate of each cell
YC	Vector	Double	$i \times 1$	Y-coordinate of each cell
coords	Matrix	Double	$i \times 2$	2-D matrix of coordinates
AM	Matrix	Double	$i \times i$	2-D initial connectivity matrix for potable water
AM1	Matrix	Double	$i \times i$	2-D initial connectivity matrix for waste water
AM2	Matrix	Double	$i \times i$	2-D admissible expansions Matrix for potable water
AM3	Matrix	Double	$i \times i$	2-D admissible expansions matrix for waste water
NE	Matrix	Double	$i \times j$	2-D investment allowance matrix for specific tech's
accuracy	Scalar	Double	unary	The precision of the MILP solver
iub	Vector	Double	unary	Imports upper bound limit
j	Vector	String	j	The technologies included in the model
maxalloweddist	Scalar	Integer	unary	Maximum allowed distance to consider a cell as neighbor
name	String	String	unary	The name of the scenario
names of cells	Vector	String	$1 \times i$	The names of the cells
ncells	Scalar	Integer	i	The number of cells in the model
resources	Vector	String	$1 \times r$	The set of resources in total in the model
pipe_resources	Vector	String	2×1	The different resources that flow in each pipe type
t	Vector	Integer	$1 \times t$	The minor time periods
Qmax	Vector	Double	$1 \times flowresources$	Upper limit on flows for each resource that can flow
RHSdef	Vector	Integer	$1 \times r(in\ demand)$	Indicates which resource has a non-zero RHS/demand
tm	Vector	String	$1 \times tm$	The major time periods (years)
OBJWT	Vector	Double	$1 \times m$	Weights of the metrics
dp	Matrix	Double	$tm \times r$	Demand % per resource per year
aac	Scalar	Boolean	unary	Flag to turn binary variables (pipe expansions) on or off
use_N	Scalar	Boolean	unary	Flag to switch pre-allocated infrastructure on or off
prod_year	Scalar	Integer	unary	The year for which production plots will take place
inv_year	Scalar	Integer	unary	The year for which investment plots will take place
full_load	Scalar	Boolean	unary	A flag to force all infrastructure work on 100% load
min_P	Scalar	Double	unary	The percentage of minimum load for all tech. infrastructure
read_ABM	Scalar	Boolean	unary	A flag to read demand values from ABM component or not
no_invest	Scalar	Boolean	unary	Flag to switch investment allowance on or off
budget	Scalar	Double	unary	Upper bound on CAPEX for investments
leak	Scalar	Double	unary	The percentage of leaks on all pipes
read_Output	Scalar	Boolean	unary	Flag to read or not the *NO.yml*
write_Output	Scalar	Boolean	unary	Flag to write or not the *NO.yml* file output
detail	Scalar	Double	1×5	Specify as flags $e.g.\{1,1,1,1,1\}$ to display in detail P, Q, L, Y, IM
waste_convert	Scalar	Double	unary	The % of clean water which results to waste water
auto_visual	Scalar	Boolean	unary	A flag to auto display visuals or not after execution
year	Scalar	String	unary	The year to match the one in the *.csv* demand filename

topology of the pipe network? How large is the CAPEX associated with pipe expansions? What is the operational cost per year and per capita? How can the total output of CO_2 for the simulated period per year be reduced or managed? What happens if a distinct connection or node (e.g. transmission pipe, facility) becomes non-functional (for instance after an environmental calamity) and what would a resilient network topology be that still allows for meeting demands? How much of the flow-resource is lost in the transport network (e.g. pipes, grids) due to leaks/losses and how does this affect results (e.g. OPEX/CAPEX/CO2)? Which novel technologies are promising to use in terms of technical specifications, costs and emissions? What is the impact on system performance metrics of existing infrastructure plans if implemented? What if we only substitute specific technologies and their numbers in specific districts or limit the expansion of some in specific and focus on different investments? How is the network topology altered if we use transport links with different flow rates/volumes?

In order to deliver insights into these questions, the user can craft the input data so as to fashion the desirable simulation. The analytical scenario is tailored by imposing limitations on resources, technologies, the flow network and policies specified by the user inside the YAML data text file. The pre-defined YAML structure as a series of tables and lists is used for this purpose, such as to inject bounds to the expansion of the pipe network, investments, flows, import of specific resource inputs needed (e.g. raw water, electricity etc.), define the weights of the metrics in the objective function (so



Launch a resilience.io module:

- ● socio-demographics
- ○ agent-based model (demand side)
- ○ RTN (supply side)

Fig. 2. The welcome screen upon launching the platform. The backbone is modular and all components can be used either individually or in combination.

as to for instance give higher priority in a solution which is more emissions-friendly), experiment with different percentages of the ABM demands, pre-allocate infrastructure and pipe network as well as upper bound each of those as desired, specify a percentage (%) of leaks on the existing pipe network, as well as defining an available budget for the total cost, among other settings.

5. Use case: *envisioning outcomes of ongoing WASH projects and steps to meet WASH targets*

The need to advance infrastructure planning capacity in Sub-Sahara African countries is evident from their uneven progress as reported in the UN Sustainable Development Agenda 2030 (United Nations General Assemply, 2015). The capital city of Ghana, Accra, and fourteen neighboring administrative districts, form the Greater Accra Metropolitan Area (GAMA). The geographic definition of GAMA as a city-region was defined by local stakeholders using the locally defined Metropolitan and Municipal District Assembly (MMDA) structures in the country (Ghana Statistical Service, 2014), from here on referred to as districts. Model calculations are carried out at the district level as a network, to enable output matching to local planning targets set in District Government Medium Term Development Plans (DMTDP), and are aggregated to the GAMA level in the results presented here.

GAMA is a rapidly growing metropolitan region where efforts to improve the water, sanitation, and hygiene (WASH) situation have yielded mixed results. Household access to improved piped water grew on average by 81% to 83% from 2000 to 2010 and access to public and private improved toilet facilities increased from 58% to 81% (Ghana Statistical Service, 2005; Bentsi-Enchill et al., 2010). However, the percentage of waste-water, including waters which contain human excreta, which was treated declined from around 10% to near zero between 2000 and 2010, whilst the population grew from three to four million people.

The city in recent years expanded potable water treatment at the Kpone site by 190,000 m^3/day, and opened a 60,000 m^3/day desalination plant, resulting in an aggregate 54% treatment capacity increase. In terms of waste-water treatment the situation has deteriorated significantly as two existing large scale treatment plants, the AMA Jamestown conventional treatment plant (16,000 m^3/day capacity) and the TEMA community 3 lagoon treatment plant (20,000 m^3/day capacity), broke down in 2004 and 2000 respectively. The majority of waste-water now ends up untreated in the environment directly or after collection and disposal. The situation is not improving as the capacity of recently opened facilities is quite small, which include a lagoon treatment plant at the University of Ghana Legon (6,400 m^3/day capacity), and a human excreta de-watering and sludge drying plant at the Lavender Hill beach site (800 m^3/day). Efforts are underway to rehabilitate the Jamestown treatment plant but have met financing difficulties.

This use case serves to demonstrate how *resilience.io* can provide knowledge support to implement macro-planning targets for GAMA to improve the WASH situation, relative to the baseline year 2010. Selected targets include those in the Sustainable Development Goals (SDGs), and the Ghana Water Sector Strategic Development Plan (WSSDP) (Ministry of Water Resources, Works and Housing, Accra, 2014) for 2012 to 2025, as developed by the Ministry for Water Resources, Works and Housing (MWRWH). The overarching urban objectives in the WSSDP plan are to increase urban water and sanitation coverage to 100% in 2025. The use case calculates what combined projects, infrastructure change, and financing needs are required to meet these goals under different scenarios, also taking into account the impact of currently ongoing projects on WASH service access once completed.

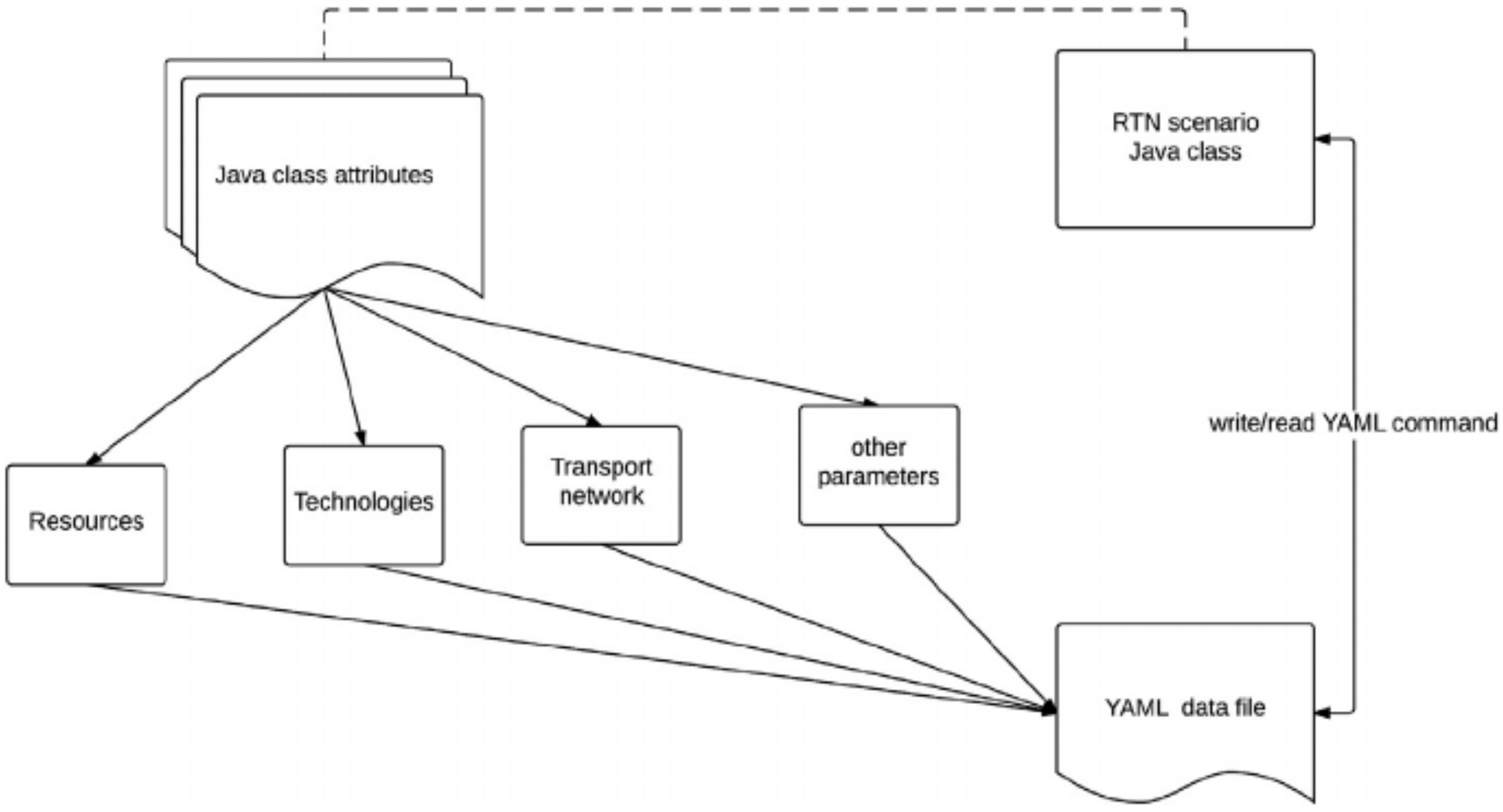


Fig. 3. Data side: The YAML serialisation language and its effective binding with Java to depict a scenario as a single Java class.

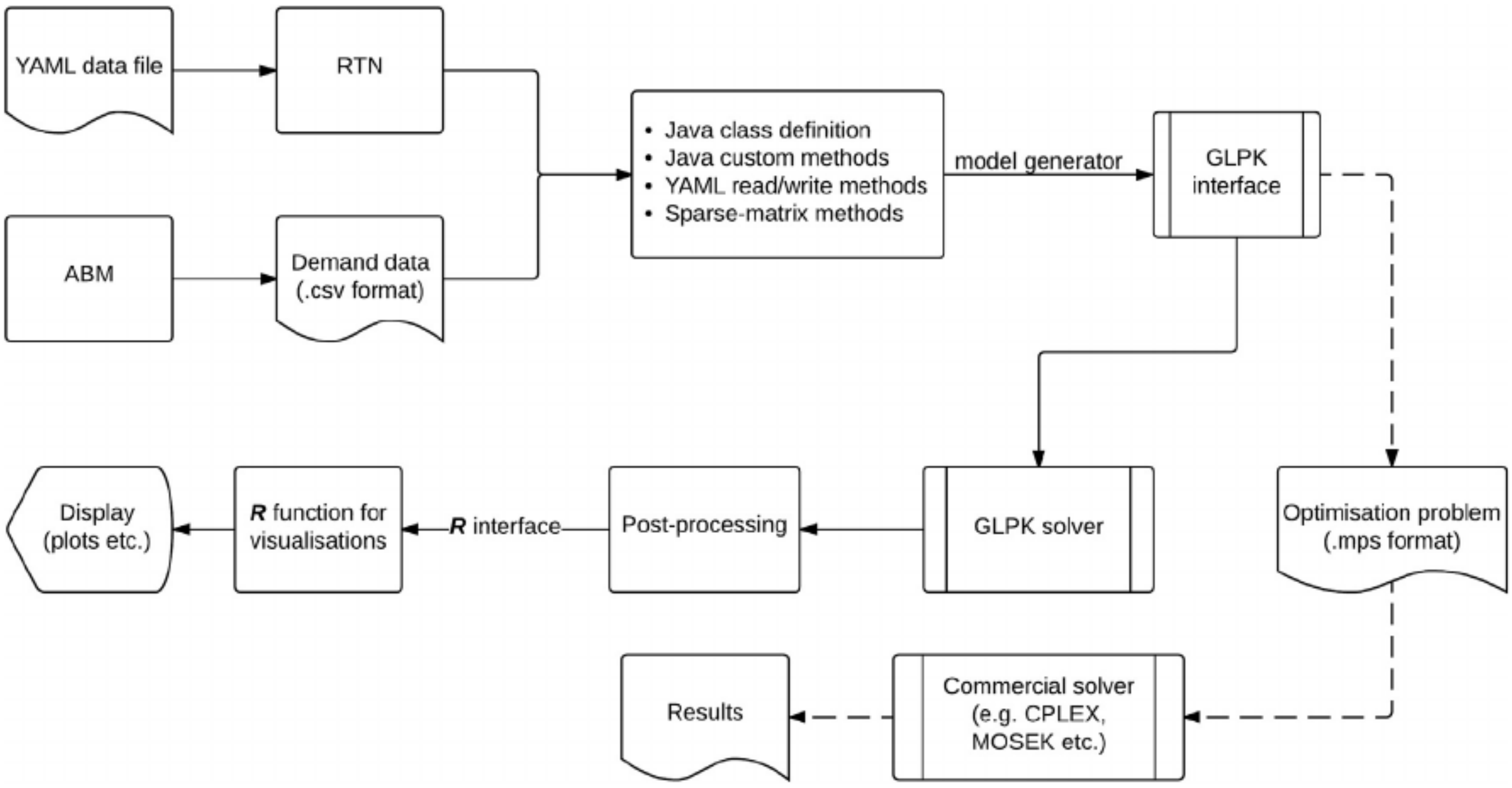


Fig. 4. The overall flow and communication of data for the implemented scheme. ABM and RTN modelling methodologies output data files which are combined inside the Java environment. A series of methods are then utilised to compose the model and through the GLPK interface to generate the optimisation (MILP) problem. Using a free commercial solver as GLPK and through R programming interface a function generates automated plots from the results in .pdf collated files at the display end-state. The dashed arrows represent an alternative path the user can use to utilise a more sophisticated and commercial solver (if available) for maybe more complex and of larger scale problems.

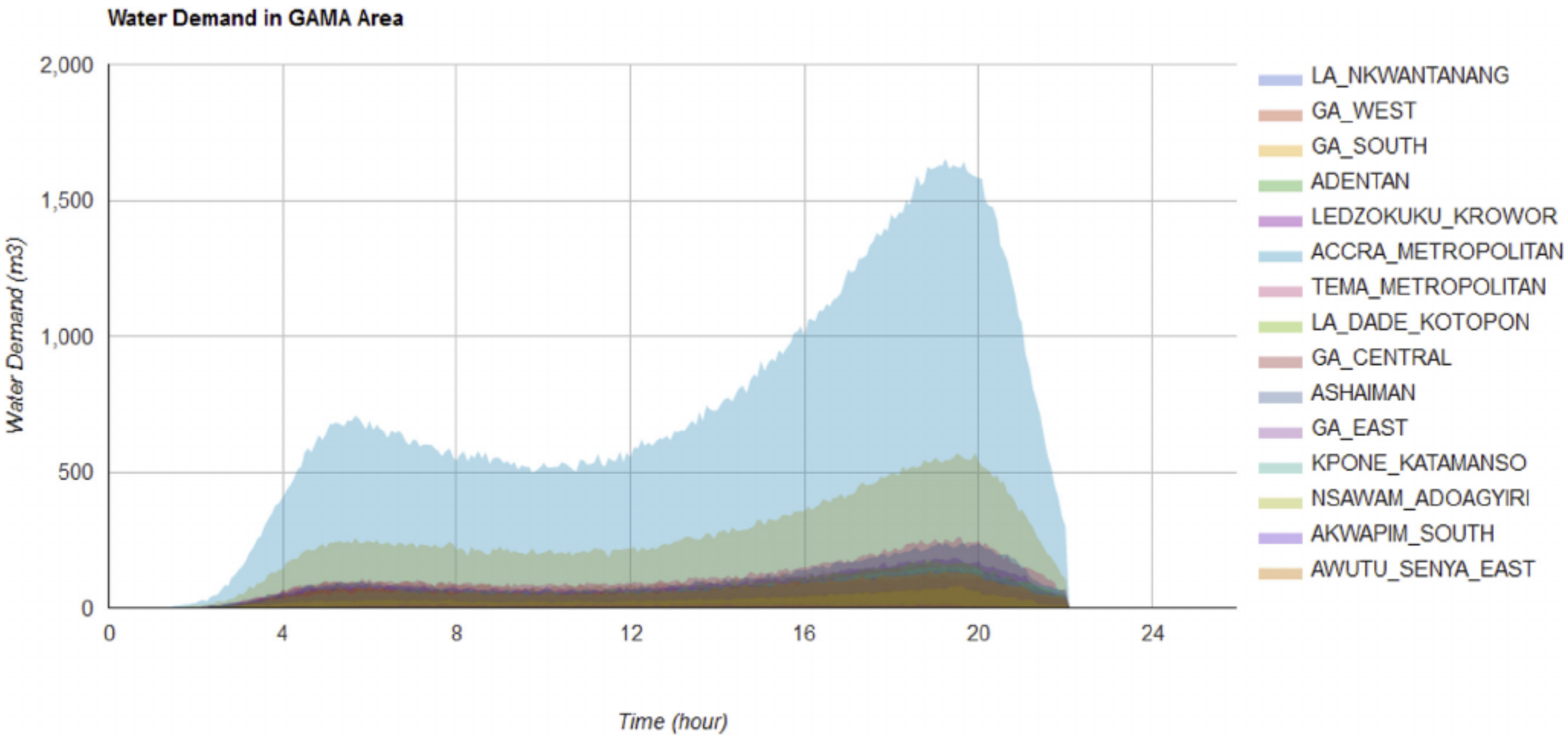


Fig. 5. Indicative total residential water demand per district over 24 h period in year 2030 (projected).

The incorporated ongoing projects (The World Bank, 2013) that we included in our simulation are: Accra Sewerage Improvement Project (ASIP), GH-GAMA Sanitation and Water Project (GH-GAMA), DANIDA Lavender Hill Sludge Treatment, Slamson Ghana Korle Lagoon cesspit treatment, Jamestown/Korle Lagoon sewerage plant rehabilitation, and the Mudor Faecal Treatment plant. Also already completed projects were added if finished after the 2010 baseline, and include: Teshie-Nungua Desalination plant, Kpong China Gezhouba and Kpong Tahal water treatment expansion.

We analysed the requirements from 2010 to 2030 to meet WASH goals across different *scenarios*: i) *WSSDP decentralised districts*, where no pipe extensions are allowed, with requirements to reach national 2025 WASH targets focusing on district level infrastructure, ii) *SDGs centralised*, with flexible pipe extensions, with requirements to reach 2030 WASH targets for the Sustainable Development Goals based on city-wide infrastructure and iii) *SDGs centralised* and *leakage reduction*, similar to the city-wide systems scenario except that leakage rates from water and waste-water pipe systems are set to 17% from the original 27% in the system from 2020 onward.

6. Results

The use case input data was based on the 2010 Ghana Census among other private and public sources. A series of technical characteristics were incorporated including pre-allocation of existing infrastructure, pipe network maps from/to districts (potable and waste-water), calibrated admissible transmission pipe and infrastructure expansions, district to district transmission pipe leakage, local tariff regulations on water use and waste-water treatment, and fifteen WASH technology data-sets including operational material and energy inputs and outputs, operational labour inputs, and financial investment and operational cost. A summary of key indicators provided by the model as outputs is shown in Table 5. Population figures in GAMA grow between 2015 and 2030 from 4.4 to 6.5 million based on the demographics calculations we performed, which included birth, death and migration rates from the Ghana census, and were calibrated to UN urban population projections.

To have a measure of comparison for our results, we use the 2000–2015 estimates of the WHO for the per person costs to reach WASH targets in Sub-Saharan Africa, summarised in their report (WHO, 2004). The prediction was that the annual cost per person receiving interventions (specifically intervention 5 is more closely linked to SDG scenario as presented here), in Table 14, would be around USD25.4. In a twenty years projection for 2010–2030 here, this would account for nearly USD762. Our calculations predict a cost of USD607 in the SDG 27% leaks scenario which is of the same order of magnitude.

6.1. Potable water

Potable water production from capacity extensions in the decentralised case rises from 0.54 to 0.85 million m^3/day between 2015 and 2030. In contrast in the SDGs infrastructure scenarios with leaks of 27% and 17%, demand grows from 0.54 (in 2015) to 0.87 and 0.76 million m^3/day (in 2030), respectively. For 2030, pipe leakage was evaluated at i) WSSDP decentralised 0.26 million ii) SDGs centralised 0.27 million and iii) SDGs centralised and leakage reduction 0.16 million m^3/day. Potable water demands without leaks were 0.58 million m^3/day in 2030. The lower SDG scenarios values arise from an optimised supply-demand infrastructure location and pipe network resulting in lower pipe water flows and thus leakage, by allowing pipe network extensions. The total investment cost in new treatment capacity by 2030 to meet 100% potable water demands is 1.5, 1.4, and 1.0 billion USD in the WSSDP decentralised, SDGs centralised, and SDGs centralised and leakage reduction scenarios, respectively. Investments were also calculated for potable and waste-water pipe network expansions at 0.11 billion USD (2010–2030) for both SDGs centralised without and with leakage reduction, respectively.

6.2. Waste-water treatment

The waste-water evaluation yielded a required 0.47 million m^3/day in treatment capacity in 2030 in all three scenarios. Concerning leaks, in 2030 2,085 m^3/day untreated waste-water pipe leakage was established for the SDG centralised scenario. Leakage is so low because waste-water treatment is found to be most cost-effective using local technologies including aerated lagoons, activated sludge and anaerobic digestion systems in each district, thereby limiting the use of district to district waste-water pipe networks. Capital expenditure for waste water treatment capacity from 2010 to 2030 for the three scenarios was 0.33, 0.33 and 0.35 billion USD. Total operational cost for 2030 including potable water treatment can be found in Table 5.

6.3. Emissions-jobs

The environmental impacts were captured by calculating total GHG emissions of the city-region WASH system. Since a small portion of waste-water is currently treated, GHG emissions from treatment infrastructure rises substantially in all scenarios. In 2015 total system emissions were 3.7 thousand tonnes, which increases to 107 thousand tonnes by 2030 in the three scenarios, primarily due to waste-water treatment growth from near 0–100%. Waste-water treatment is fairly GHG-intensive due to micro-organisms turning sludge into either carbon dioxide or methane, which ends up into the environment. The calculations do not take into account what happens with untreated waste-water that ends up in the environment as a baseline, since a portion will naturally decompose aerobically or anaerobically in the environment by micro-organisms. The total system GHG emissions in $kg\ CO2\ equivalent/m^3$ of treated water and waste-water in 2030 are 81, 80 and 87 thousands of tonnes correspondingly.

Total jobs for all water and waste-water treatment and distribution grow from 2,743 in 2015 to 3,253, 4,380 and 3,862 jobs by 2030 in the WSSDP decentralised, SDGs centralised and SDGs centralised and leakage reduction scenarios, respectively.

Table 5
Results generated for the examined use case in three different scenarios for 2010–2030. Financial values in 2015 USD dollars.

Platform-calculated indicators	Decentralised	SDGs 27% leaks	SDGs 17% leaks
Projected population (millions) in 2030	6.49	6.49	6.49
Total GAMA potable water demands gross of leaks (m^3 per day) in 2030	844,938	855,523	748,575
Total GAMA potable water leakage in pipes (m^3 per day) in 2030	260,298	270,883	163,935
Pipe extensions suggested 2010–2030 for potable water (MMDA to MMDA)	0	3	4
Additional conventional water treatment capacity (m^3 per day)	459,000	433,500	306,000
Total GAMA waste-water treatment (m^3 per day) in 2030	467,711	467,711	467,717
Pipe extensions suggested 2010–2030 for waste-water (MMDA to MMDA)	0	1	0
Total GAMA waste-water leakage in pipes (m^3 per day) in 2030	0	2,085	0
CAPEX (all CAPEX values in billion USD) 2010–2030	4.73	3.94	3.62
CAPEX for on-going and complete infrastructure projects 2010–2020	2.55	2.55	2.55
CAPEX for water treatment infrastructure 2010–2030	1.85	0.93	0.61
CAPEX for waste-water treatment infrastructure 2010–2030	0.33	0.33	0.35
CAPEX for pipe expansions in potable, waste-water networks 2010–2030	0	0.13	0.11
CAPEX per person 2010–2030 (USD)	729	607	558
OPEX in 2015 (million USD)	90.6	90.6	67.9
OPEX in 2030 (million USD)	234.6	200.6	187.9
OPEX for electricity inputs in 2030 (million USD)	21.5	20.4	19.9
OPEX per person in 2030 (USD)	30.39	24.6	23.3
Total CO_2 emissions in 2030 (thousands of tonnes)	107	107	107

7. Discussion

The functionality in the presented *resilience.io* platform use case can be compared to IUWCM and IUWSM models, since *resilience.io* covers the water and waste-water demand and supply cycle, is able to incorporate other resource and pollutant vectors, labour requirements, and allows MILP optimisation over both economic and environmental indicators, in the use case using greenhouse gas emissions. Our optimisation approach allows exploration of WASH system design by setting minimum performance criteria. This is different from previous approaches like in WaterMet2 and UWOT which calculate the performance of user defined designs and interventions.

Particular differences of WaterMet2 to *resilience.io* are i) the approach is to test human designed plans as opposed to finding optimised supply resource-technology system configurations, ii) a fixed set of treatment technologies with input-output vectors, as opposed to flexible introduction of new technologies in *resilience.io* based on matrix insertion, and iii) a limit to daily time-steps to settle supply and demand instead of hourly.

Particular differences of UWOT to *resilience.io* are i) the focus is on potable water supply and does not include waste-water treatment, ii) the approach is to test the optimal operation of a user input based pipeline-reservoir-treatment system given a set of simulation demands as opposed to allowing for finding optimised entirely new network-technology configurations, iii) UWOT allows for appliance fixed household location demand as opposed to more flexible spatially mobile agents activity based demands. The *distinct advantages* of our approach are that:

- The platform is built for release as non-commercial software;
- We use behavioral modelling in a multi-agent system to generate demands which enables simulations that can exploit fine-grained variations in spatially defined variables of a population (Bonabeau, 2002; Bousquet and Page, 2004) (multi-user type variation, as regarded effective in this context (Rixon et al., 2007));
- We provide decision support for supply solutions via mathematical programming optimisation (Guignard-Spielberg and Spielberg, 2005) that can be tailored to specific sustainability needs for technology investment and operation, due to flexible input-output dimensions for each technology, and a flexible multi-criteria objective function;
- Our implementation is data-driven and neither system (sector) nor region bounded, and can be utilised in any city-region for any *demand-supply-flow* context, with the possibility of system specific functionality expansions.

The *main limitations* of the current state of the platform are that:

- We do not yet cover all WASH system features, in particular water flow quality characterisation, natural water reservoir stock dynamics and atmospheric water flows like storm-water and flooding;
- We do not provide automated functionality to rapidly evaluate the impacts of parameter uncertainties on WASH system design scenario outcomes;
- The platform is mainly usable by expert users due to the high level of technical detail involved, combined with a text line data entry implementation.

8. Conclusions

The *resilience.io* platform results showed, at a practical application level, the possibilities of fine grained modelling of population characteristics, technological facilities, and associated resource and waste flows in space and time, to provide insights for more resilient city-region systems planning within a broader scope of economic, social and environmental metrics. In particular support was demonstrated for:

- Evaluation of future infrastructure needs for population and economic scenarios,
- Provisioning of total cost estimates to meet national and SDG targets,
- Visibility on environmental and social decision criteria such as jobs and GHG emission impacts and
- Evaluation and prioritisation of planning options by quantifying differences between i) infrastructure expansion and (pipe) network layout changes versus ii) substantial reduction in transport network losses.

At a technical level the feasibility of an open-source based implementation of an ABM coupled to a MILP optimisation model was demonstrated. It can simulate the demand and resource flow based supply dynamics for integrated economic and environmental modelling purposes in a city-region of several million people. The implementation also shows the importance of a flexible design. Without adjusting the model structure, but by changing only the input data file and then running the model again, key adjustments can be evaluated in technology, flow network and policy settings. The multi-objective criteria that are minimised can also be altered and can include both economic and environmental objectives.

The platform was also found to have emerging benefits from the inclusion of population, income and labour aspects. These aspects enabled the evaluation of the capacity a city-region needs to implement proposed solutions at a decentralised government level. This is achieved by quantifying labour needs and operational revenue flow requirements. Capacity at a financial, labour and planning level is of particular concern for the sustainable development of low to lower middle income countries. For example, in Ghana for which the use case was built, the district governments are responsible for waste-water treatment. However, these governments receive low tax revenues due to a large informal sector, resulting in low staffing (less than one local government staff per 1000 people versus 5+ for high income countries), and limited ability to attract national government or private sector finance.

Future work includes the extension of the platform to support uncertainty in the modelling formulation for various parameters (such as capital and operational expenditure or the magnitude of demand in resources) and the design of a Graphical User Interface dedicated to generate YAML data files and expand visual output possibilities in a faster and user friendly way, to enable uptake outside of the expert user community. Embedding different optimisation solvers to explore efficiency is also an interesting avenue.

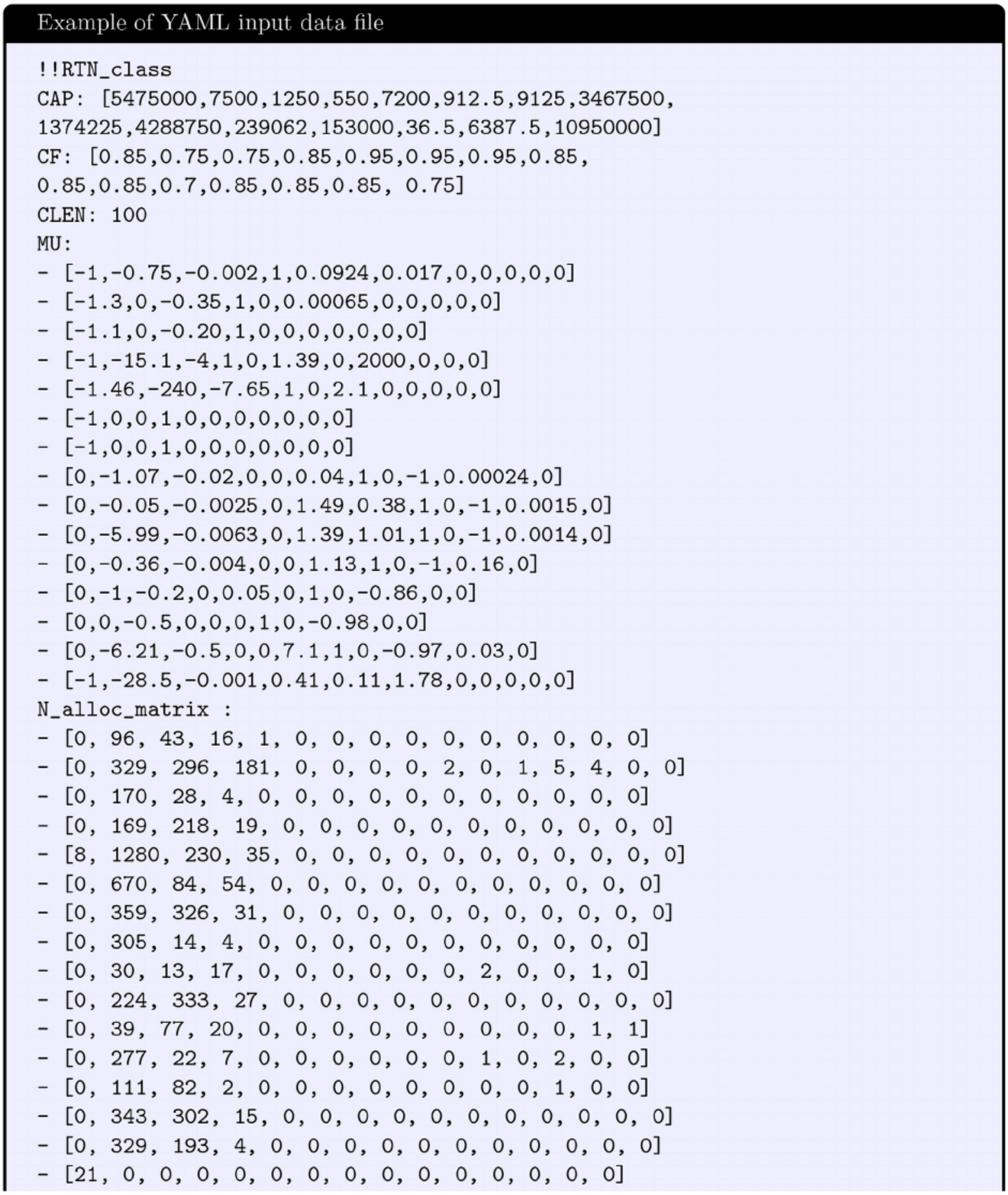
Acknowledgments

A prodigious debt of gratitude goes to the Department for International Development (UK) for funding this activity under the Future Cities Africa project (grant number 203830). We also thank the Ecological Sequestration Trust (The Ecological Sequestration Trust, 2017) for arranging several webinars with local stakeholders from Ghana and the platform demonstration debut (June 16 at Ghana), the Cities Alliance International (Cities Alliance, 2017) and Ghana team for their management support, project debut workshop, and insightful inputs. Also, local experts from

Ghana Foster Mensah,[3] Sampson Madana, Arthur Bernard and Ohene Ofori among many others, were of immense help in data contributions and use case input.

Appendix

An example of a scenario in YAML data is given below as well as some automated graphical visual outputs from the platform are demonstrated below:



Example of YAML input data file

```
!!RTN_class
CAP: [5475000,7500,1250,550,7200,912.5,9125,3467500,
1374225,4288750,239062,153000,36.5,6387.5,10950000]
CF: [0.85,0.75,0.75,0.85,0.95,0.95,0.95,0.85,
0.85,0.85,0.7,0.85,0.85,0.85, 0.75]
CLEN: 100
MU:
- [-1,-0.75,-0.002,1,0.0924,0.017,0,0,0,0,0]
- [-1.3,0,-0.35,1,0,0.00065,0,0,0,0,0]
- [-1.1,0,-0.20,1,0,0,0,0,0,0,0]
- [-1,-15.1,-4,1,0,1.39,0,2000,0,0,0]
- [-1.46,-240,-7.65,1,0,2.1,0,0,0,0,0]
- [-1,0,0,1,0,0,0,0,0,0,0]
- [-1,0,0,1,0,0,0,0,0,0,0]
- [0,-1.07,-0.02,0,0,0.04,1,0,-1,0.00024,0]
- [0,-0.05,-0.0025,0,1.49,0.38,1,0,-1,0.0015,0]
- [0,-5.99,-0.0063,0,1.39,1.01,1,0,-1,0.0014,0]
- [0,-0.36,-0.004,0,0,1.13,1,0,-1,0.16,0]
- [0,-1,-0.2,0,0.05,0,1,0,-0.86,0,0]
- [0,0,-0.5,0,0,0,1,0,-0.98,0,0]
- [0,-6.21,-0.5,0,0,7.1,1,0,-0.97,0.03,0]
- [-1,-28.5,-0.001,0.41,0.11,1.78,0,0,0,0,0]
N_alloc_matrix :
- [0, 96, 43, 16, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 329, 296, 181, 0, 0, 0, 0, 2, 0, 1, 5, 4, 0, 0]
- [0, 170, 28, 4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 169, 218, 19, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [8, 1280, 230, 35, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 670, 84, 54, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 359, 326, 31, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 305, 14, 4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 30, 13, 17, 0, 0, 0, 0, 0, 0, 2, 0, 0, 1, 0]
- [0, 224, 333, 27, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 39, 77, 20, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]
- [0, 277, 22, 7, 0, 0, 0, 0, 0, 0, 1, 0, 2, 0, 0]
- [0, 111, 82, 2, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0]
- [0, 343, 302, 15, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [0, 329, 193, 4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
- [21, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
```

---

[3] Centre for Remote Sensing and Geographic Information Services, University of Ghana, Legon, Annie-Jiagge Road, Accra, Ghana.

```
ODS:
- [4632193 , 3705754]
- [89126797 , 71301437]
- [11961616 , 9569293]
- [7504044 , 6003235]
- [8506051 , 6804841]
- [28814317 , 23051454]
- [12085454 , 9668363]
- [6670931 , 5336745]
- [8770558 , 7016447]
- [6908802 , 5527041]
- [9799336 , 7839469]
- [12679806 , 10143845]
- [3126596 , 2501277]
- [5024429 , 4019543]
- [1550251 , 1240201]
- [1,1]
PHI: [1752,7008]
VI:
- [0,0,0]
- [0,0.020,0]
- [0,2.4,0]
- [0,0,0]
VIJA:
- [45197947,0,0]
- [3325541,0,0]
- [50000,0,0]
- [43065,0,0]
- [2478334,0,0]
- [150,0,0]
- [100,0,0]
- [53398778,0,0]
- [14145810,0,0]
- [768544,0,0]
- [1516850,0,0]
- [4816845,0,0]
- [3092,0,0]
- [244500,0,0]
- [130000000,0,0]
VPJ:
- [0,0.23,0.017]
- [0,0.237,0.0065]
- [0,1,0]
- [0,25.6,1.39]
- [0,302,2.1]
```

```
- [0,1,0]
- [0,1,0]
- [0,0.19,0.04]
- [0,0.255,0.38]
- [0,0.56,1.01]
- [0,0.206037736,0]
- [0,1.63,0]
- [0,0.07,0]
- [0,1.21,0]
- [0,1.5,0]
VQ:
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
- [0,0,0]
VY:
- [2350000,0,0]
- [235000,0,0]
XC: [-0.132, -0.220, -0.036, -0.297,-0.404, -0.310, -0.219,
 -0.057,-0.158, -0.167, -0.107, -0.044,-0.234, -0.446, -0.347, 0.062]
YC: [5.695, 5.575, 5.700, 5.615, 5.642,5.710, 5.699,
5.756, 5.587, 5.745, 5.602, 5.650, 5.860, 5.577, 5.825,6.169]
coords:
- [-0.132, 5.695]
- [-0.220, 5.575]
- [-0.006, 5.680]
- [-0.297, 5.615]
- [-0.404, 5.642]
- [-0.310, 5.710]
- [-0.219, 5.699]
- [-0.057, 5.756]
- [-0.158, 5.587]
- [-0.167, 5.745]
- [-0.107, 5.602]
- [-0.044, 5.650]
- [-0.234, 5.860]
- [-0.446, 5.577]
- [-0.347, 5.825]
```

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- [0.062,6.169]
NE :
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- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [1,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [0,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
- [1,1,1,1,1,0,0,1,1,1,1,1,1,1,1]
AM :
- [0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [1,0,0,1,0,1,1,0,1,1,1,0,0,0,0,0]
- [0,0,0,0,0,0,0,1,0,0,0,1,0,0,0,0]
- [0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0]
- [0,1,0,1,0,0,0,0,0,0,0,0,0,1,0,0]
- [0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,1,0,0,0,1,0,0,0,0,0,0]
- [0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0]
- [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0]
AM1 :
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
```

```
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
AM2 :
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
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- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
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- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
- [0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0]
AM3 :
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
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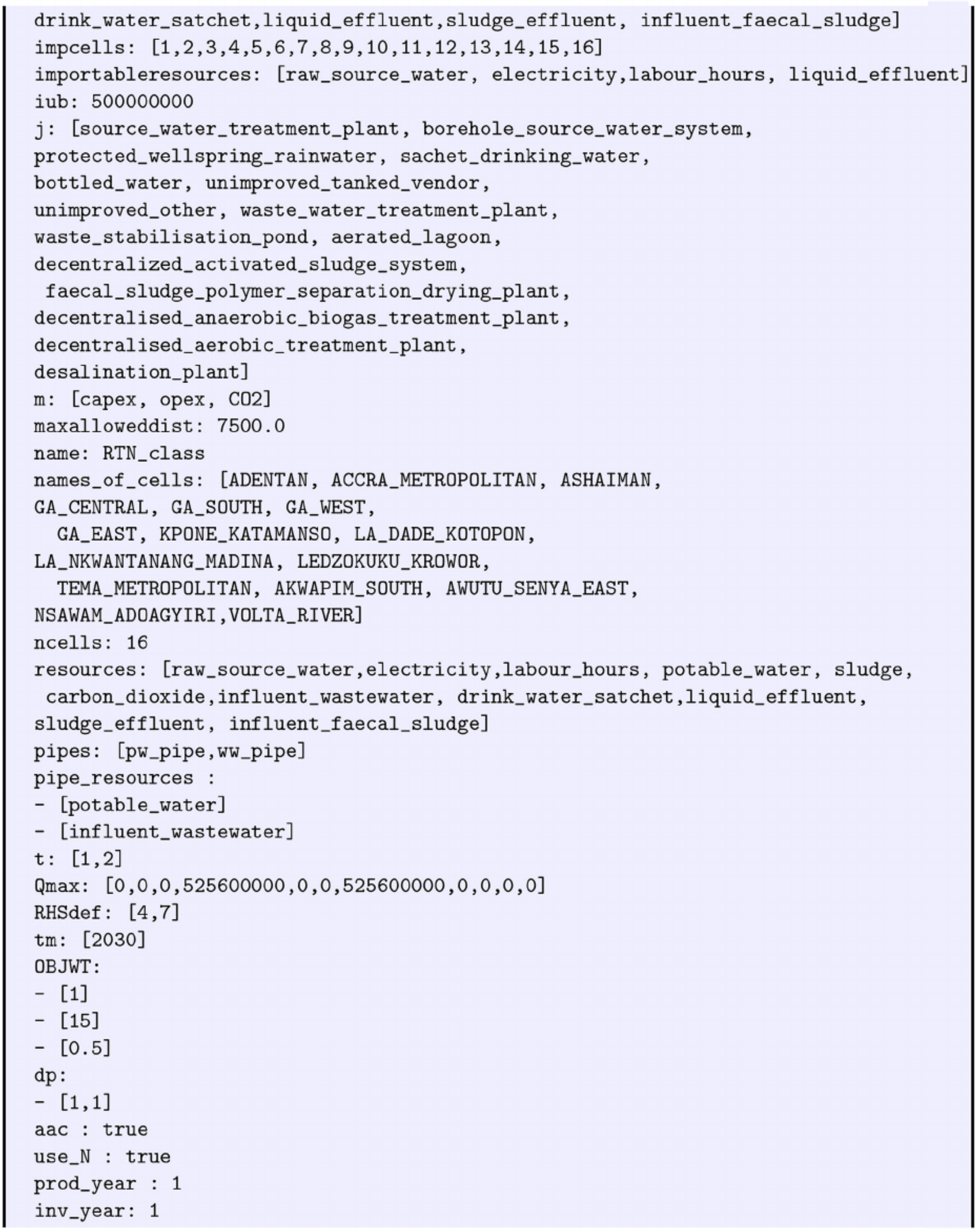
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
- [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0]
- [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
year : 2030
accuracy: 0.0005
flowresources: [raw_source_water,electricity,labour_hours,
potable_water, sludge, carbon_dioxide,influent_wastewater,
```



```
drink_water_satchet,liquid_effluent,sludge_effluent, influent_faecal_sludge]
impcells: [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16]
importableresources: [raw_source_water, electricity,labour_hours, liquid_effluent]
iub: 500000000
j: [source_water_treatment_plant, borehole_source_water_system,
protected_wellspring_rainwater, sachet_drinking_water,
bottled_water, unimproved_tanked_vendor,
unimproved_other, waste_water_treatment_plant,
waste_stabilisation_pond, aerated_lagoon,
decentralized_activated_sludge_system,
 faecal_sludge_polymer_separation_drying_plant,
decentralised_anaerobic_biogas_treatment_plant,
decentralised_aerobic_treatment_plant,
desalination_plant]
m: [capex, opex, CO2]
maxalloweddist: 7500.0
name: RTN_class
names_of_cells: [ADENTAN, ACCRA_METROPOLITAN, ASHAIMAN,
GA_CENTRAL, GA_SOUTH, GA_WEST,
  GA_EAST, KPONE_KATAMANSO, LA_DADE_KOTOPON,
LA_NKWANTANANG_MADINA, LEDZOKUKU_KROWOR,
  TEMA_METROPOLITAN, AKWAPIM_SOUTH, AWUTU_SENYA_EAST,
NSAWAM_ADOAGYIRI,VOLTA_RIVER]
ncells: 16
resources: [raw_source_water,electricity,labour_hours, potable_water, sludge,
 carbon_dioxide,influent_wastewater, drink_water_satchet,liquid_effluent,
sludge_effluent, influent_faecal_sludge]
pipes: [pw_pipe,ww_pipe]
pipe_resources :
- [potable_water]
- [influent_wastewater]
t: [1,2]
Qmax: [0,0,0,525600000,0,0,525600000,0,0,0,0]
RHSdef: [4,7]
tm: [2030]
OBJWT:
- [1]
- [15]
- [0.5]
dp:
- [1,1]
aac : true
use_N : true
prod_year : 1
inv_year: 1
```

```
full_load : false
min_P : 0.5
read_ABM : true
no_invest : false
budget : 500000000000
leak : 0.27
read_Output : false
write_Output : true
detail: [1,1,1,1,1]
waste_convert : 0.8
auto_visual : false
```

A small part of an .mps formulation of the MILP RTN optimisation problem for the SDG’s 2030 27% leaks scheme is shown below. All variables and constraints appear in a friendly naming policy to be easily identified (for instance for debugging reasons):

Example of .mps ouput file from RTN module

```
* Problem:    RTN_class
* Class:      MIP
* Rows:       2996
* Columns:    4068 (960 integer, 397 binary)
* Non-zeros:  12700
* Format:     Free MPS
*
NAME RTN_class
ROWS
 N R0000000
 E TBal(’source_water_treatment_plant’.ADENTAN.2030)
 E TBal(’source_water_treatment_plant’.ACCRA_METROPOLITAN.2030)
 E TBal(’source_water_treatment_plant’.ASHAIMAN.2030)
 E TBal(’source_water_treatment_plant’.GA_CENTRAL.2030)
 E TBal(’source_water_treatment_plant’.GA_SOUTH.2030)
 ...
```

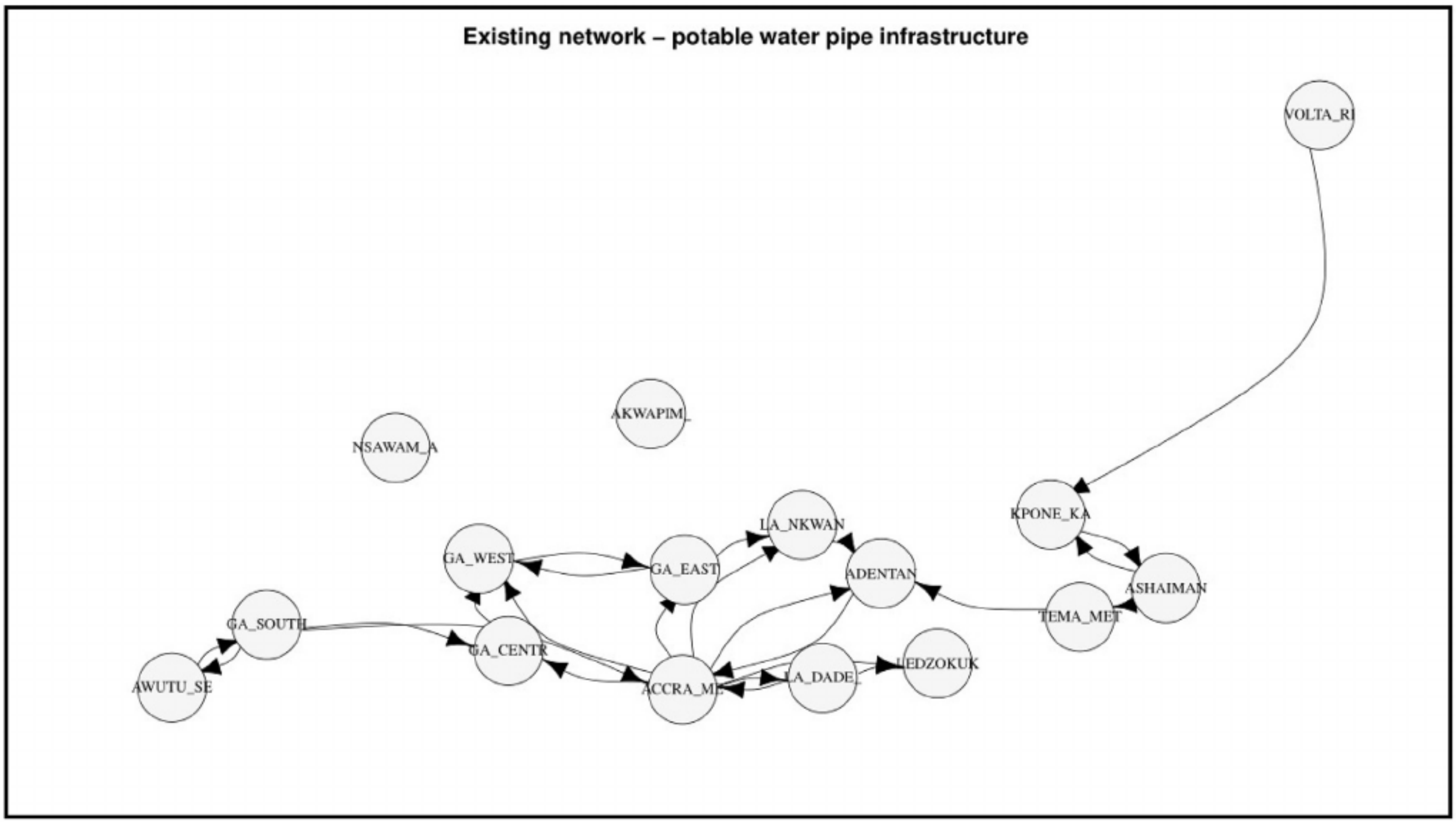


Fig. 6. An example of automated visual outputs from the platform; geo-localised districts in GAMA showing the initial pipe network for potable water.

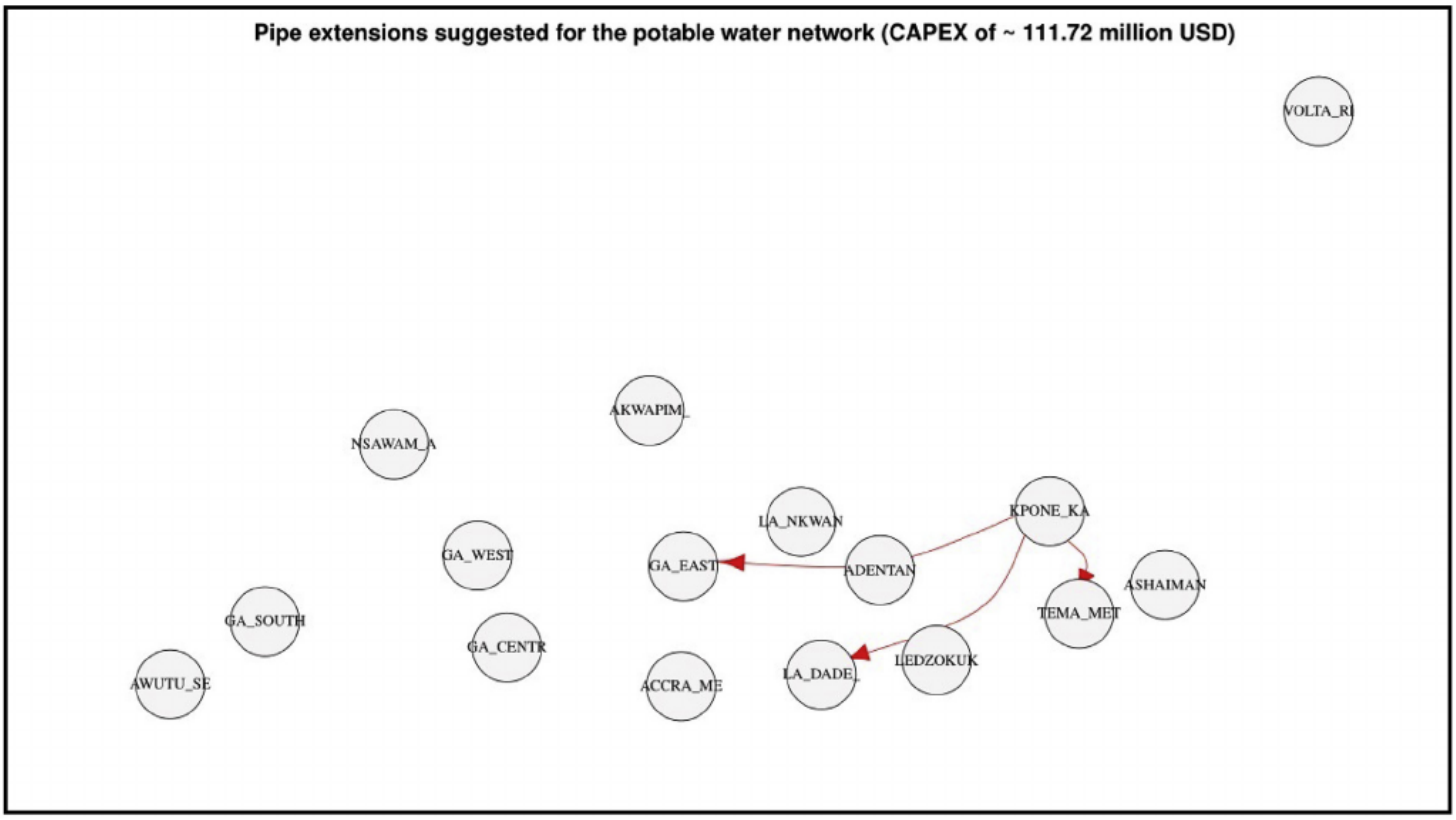


Fig. 7. The suggested by the platform expansions for 2030 in the SDG's 27% leaks scheme, in red arcs, to satisfy more efficiently the demands. The expansions take into account the cost of pipe construction per meter of the respective distance between districts.

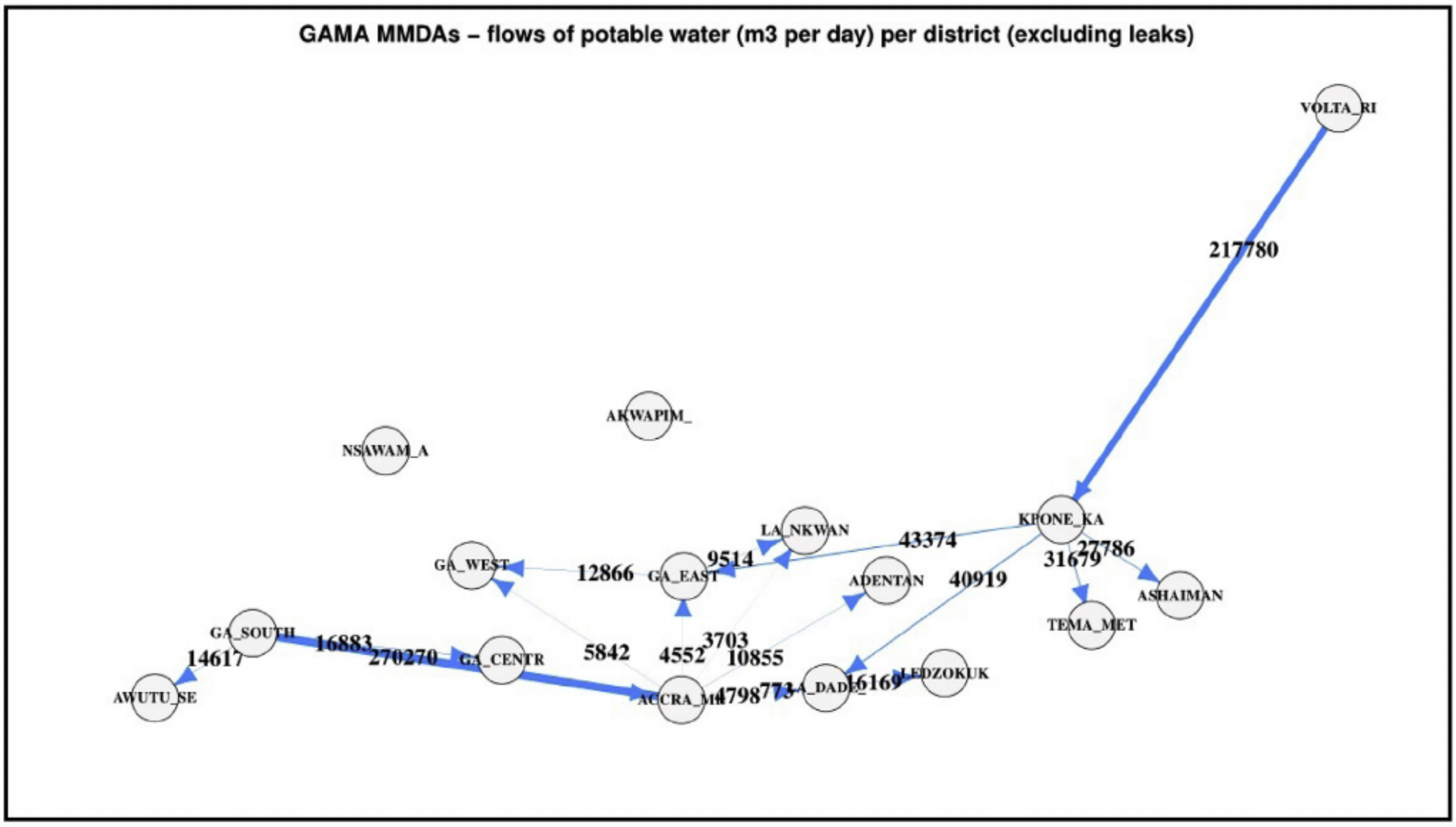


Fig. 8. The optimal flows of potable water for 2030 in the SDG's 27% leaks scheme.

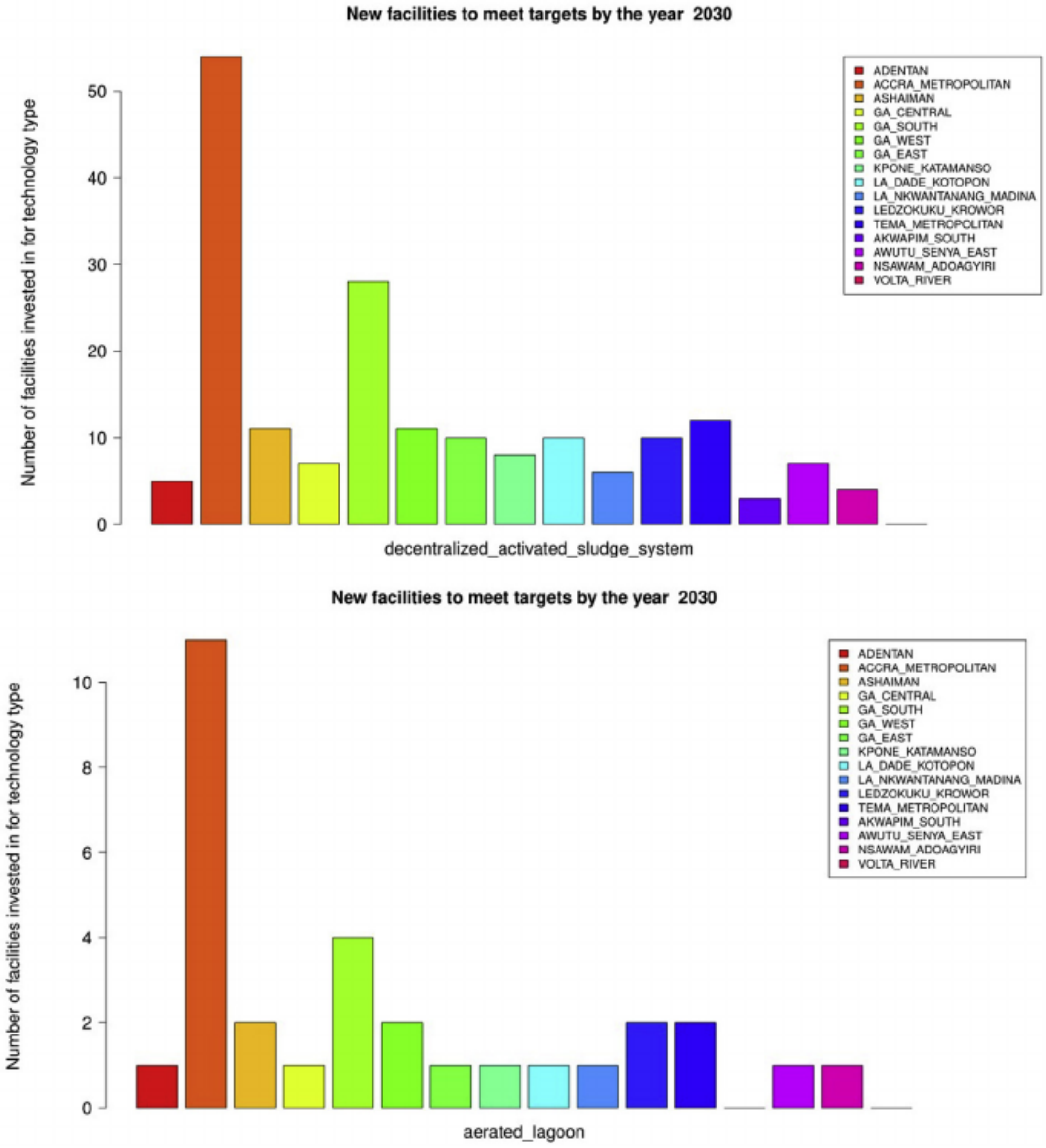


Fig. 9. Decentralised districts scenario in 2030 projection; a large amount of aerated lagoons and decentralised activated sludge systems, to facilitate the waste-water treatment across GAMA.

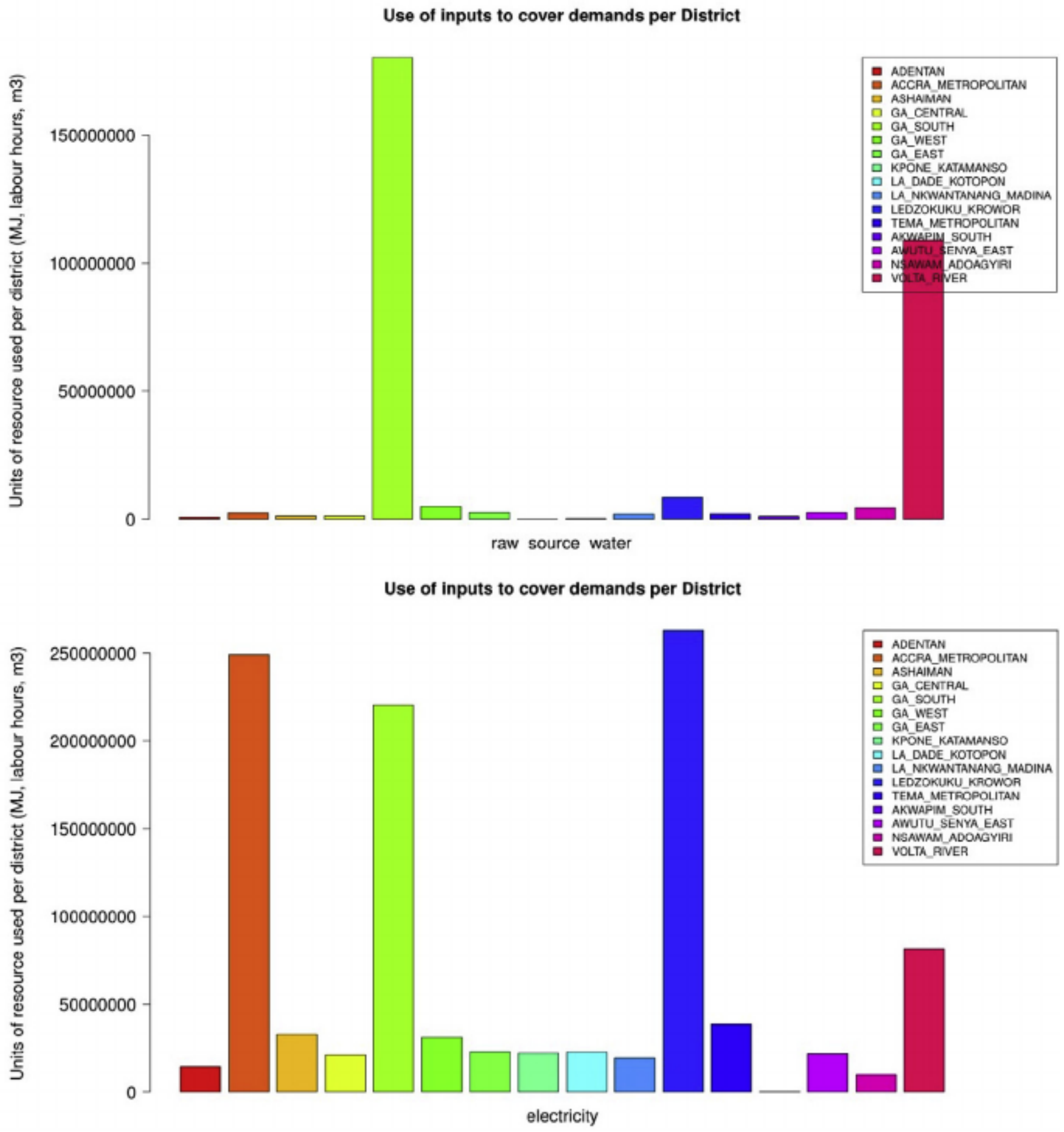


Fig. 10. 2030 in the SDG's 27% leaks scheme inputs of raw water and electricity, to meet 100% demands.

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