## Research Paper

# Decision support system for selection of appropriate water supply and sanitation technologies in developing countries

Ali Bouabid and Garrick Louis

## ABSTRACT

Access to water supply and sanitation services remains a challenge in many parts of the world. The expected growth of the world's population, from about 7.8 billion people today to 9.8 billion people by 2050, and to around 11 billion people by the end of 2100, will create even higher demand and a greater strain on these basic services. Goal 6 of the United Nations Sustainable Development Goal (SDG) aims to 'Ensure availability and sustainable management of water and sanitation for all' by 2030. However, in a recent report, UN-Water warns us that if things continue on the current path, the world will miss the targets of SDG 6. The selection of appropriate water and sanitation technologies is key to meeting SDG 6 targets. This paper presents an original framework of a decision support system (DSS) for the selection of appropriate water supply and sanitation (Watsan) technologies in developing countries. The proposed DSS has three components. The first component is the user interface, where the inputs are the assessment of a community's capacity to manage a given water supply or sanitation system, and its regional specificity. The second component of the DSS is a database of Watsan technologies classified according to the capacity requirement level (CRL) metric, and finally, the third component is a matching algorithm for the selection of appropriate Watsan technology options. Case studies and simulations results are presented for the evaluation of the performance of the decision support system.

**Key words** | community capacity assessment, decision support system, Sustainable Development Goals, sustainable infrastructure, water and sanitation systems

**Ali Bouabid** (corresponding author)
Industrial and Systems Engineering Department,
Khalifa University,
Abu Dhabi,
United Arab Emirates
E-mail: *ali.bouabid@ku.ac.ae*

**Garrick Louis**
Department of Engineering Systems and Environment,
University of Virginia,
Charlottesville, VA,
USA

## HIGHLIGHTS

- A decision support system (DSS) is used for the selection of appropriate Watsan technologies.
- A capacity factor analysis (CFA) is used for the assessment of the community's capacity to operate a Watsan service sustainably.
- A database of Watsan technologies classified by capacity requirement level (CRL) is used.
- A matching model uses an algorithm to match a community to a set of appropriate Watsan technologies.



doi: 10.2166/washdev.2021.203

## INTRODUCTION

Access to water supply and sanitation services is still a challenge for too many people around the world today. Despite significant efforts during the past four decades, the recent assessment of the WHO/UNICEF Joint Monitoring Program (JMP) shows that only 71% of the world's population uses a safely managed drinking water service. The situation is even more dire for access to safely managed sanitation services, where only 45% of the world's population enjoys such access (WHO/UNICEF 2017). There are many reasons why so many people lack access to these basic services, among them we can cite poverty and inequality, poor governance, and population increase. On this last point, the world's population is expected to grow from a current population of about 7.8 billion people to about 9.8 billion people by 2050, and to around 11 billion people by the end of this century (Roser 2020). This growth will create even higher demand and will result in a greater strain on water supply and sanitation services. The United Nations (UN) has recognized access to water and sanitation services as a human right since 2010 (United Nations 2010). Furthermore, in 2015, the UN established 17 Sustainable Development Goals (SDGs) to 'achieve a better and more sustainable future for all'. Among them, SDG 6 aims to 'Ensure availability and sustainable management of water and sanitation for all' by 2030 (United Nations 2015). In its most recent report, 'World Water Development' (UNESCO 2019), UN-Water reports that there are currently three out of ten people who do not have access to safe drinking water, and six out of ten people without access to sanitation services. Furthermore, the report notes that if things continue on this path, SDG 6 will not be reached as expected by 2030.

Appropriate technology for water supply and sanitation (Watsan) infrastructure is key for sustained access to these basic services. We define appropriate technology as a technology that satisfies the needs of the user, and which the user can acquire, operate, and maintain with the user's resources. Current approaches for the selection of Watsan technologies in developing communities have a high failure rate. For example, in a recent update on the situation of water supply systems in Africa, the Rural Water Supply Network (RWSN) (Banks & Furey 2016) reports that an average of 22% of water points are not functional across 11 countries surveyed. Furthermore, the report noted a high rate of failure early after the installation; almost 15% after the first year, and around 25% 4 years after the installation.

To address the challenge of sustainable access to water supply and sanitation in developing countries, this paper proposes a new framework of a decision support model for the selection of appropriate water supply and sanitation technology options.

## CURRENT DECISION TOOLS

Many decision support tools are available to assist Watsan professionals and international development agencies in the selection, implementation, and maintenance of technologies for water supply and sanitation services. Palaniappan *et al.* (2008) completed a review of 120 existing support resources for the selection of Watsan technologies. Five types of support tools were identified: evaluation tools, process guides, technical briefs, technical references, and policy papers. After reviewing these 120 decision support resources, Palaniappan *et al.* (2008) selected 18 of them that provide the most comprehensive decision-making supports to water and sanitation practitioners. Table 1 presents these support resources that are the closest to an optimal water supply and sanitation decision-making support tool. Within these 18 support resources, four important components were identified by Palaniappan, as they constitute the key characteristics of an ideal decision-making support tool: Sector, Locale, Topics, and User.

The definitions of these four components, as provided by Palaniappan *et al.* (2008), are reported below:

- 'Sector represents the area of focus of the support resources such as water supply, drinking water treatment, sanitation, wastewater treatment, and hygiene.

**Table 1** | List of the most comprehensive water supply and sanitation support resources (Palaniappan *et al.* 2008)

| Authors | Decision support resources |
|---|---|
| Australian Agency for International Development | Safe water guide for the Australian aid program (2005) |
| Brikké, F. and Bredero M. | Linking technology choice with O&M in the context of community water supply and sanitation (WHO 2003) |
| Cotruvo, J. *et al.* | Providing safe drinking water in small systems: Technology, operations, and economics (NSF, WHO and PAHO 1999) |
| Department of Water Affairs and Forestry, South Africa | Introductory guide to appropriate solutions for water and sanitation (2004) |
| Deverill *et al.* | Designing water supply and sanitation projects to meet demand in rural and peri-urban communities (2002) |
| Huuhtanen, S. and Laukkanen, A. | Guide to working in sanitation and hygiene for those working in developing countries (2006) |
| Lantage *et al.* | Household water treatment and safe storage options in developing countries: Review of current implementation practices (2007) |
| ROLAC – UNEP | Recommendations on basic sanitation and municipal wastewater for Latin America & the Caribbean (2003) |
| Skinner, B. – WELL | Small-scale water supply: a review of technologies (2003) |
| Smet, J. Van Wijk, C. IWSC | Small community water supplies (2002) |
| UNEP | International source book on environmentally sound technologies for wastewater and storm water management (2000) |
| UNICEF | Towards better programming: A sanitation handbook (1997) |
| Finney, B.A. and Gearheart, R.A – U. of Humboldt | Water and wastewater technologies appropriate for reuse model |
| WELL | Guidance document on water supply and sanitation programmes (1998) |
| World Bank | Manual on low-cost sanitation technologies for Ger Areas, Mongolia (2006) |
| WSP and WUP | Water and sanitation for all: A practitioners' 'companion' (2003) |

- Locale indicates a support resource that targets the location of the community, which is captured by the regional specificity and the types of communities (rural, peri-urban, and urban).
- Topics, includes information on construction, O&M, community involvement, cost, evaluation and monitoring, scalability and replicability, and case studies.
- User refers to the user interface of the support resource that allows users to specify the conditions of the community through inputs to provide outputs that are relevant based on the community's conditions.

The conclusion of this review shows that there exists a need for a decision-making support tool to assist Watsan practitioners in identifying, evaluating, and choosing a technology option that best suits the conditions and needs of a community. The most common missing elements among the decision support resources evaluated were social factors, regional specificity (RS), project replicability, and an effective user interface. Other missing items were information on cost and financing.

The decision support model proposed in this research addresses most of the missing elements identified by Palaniappan *et al.* (2008) and it is presented in the next section.

## PROPOSED DECISION MODEL

The framework of the decision model described hereafter is presented in Figure 1. It is the result of ongoing research carried out by the authors on the issue of sustainable access to water supply and sanitation services in developing communities. The decision model has three modules: Assessment,

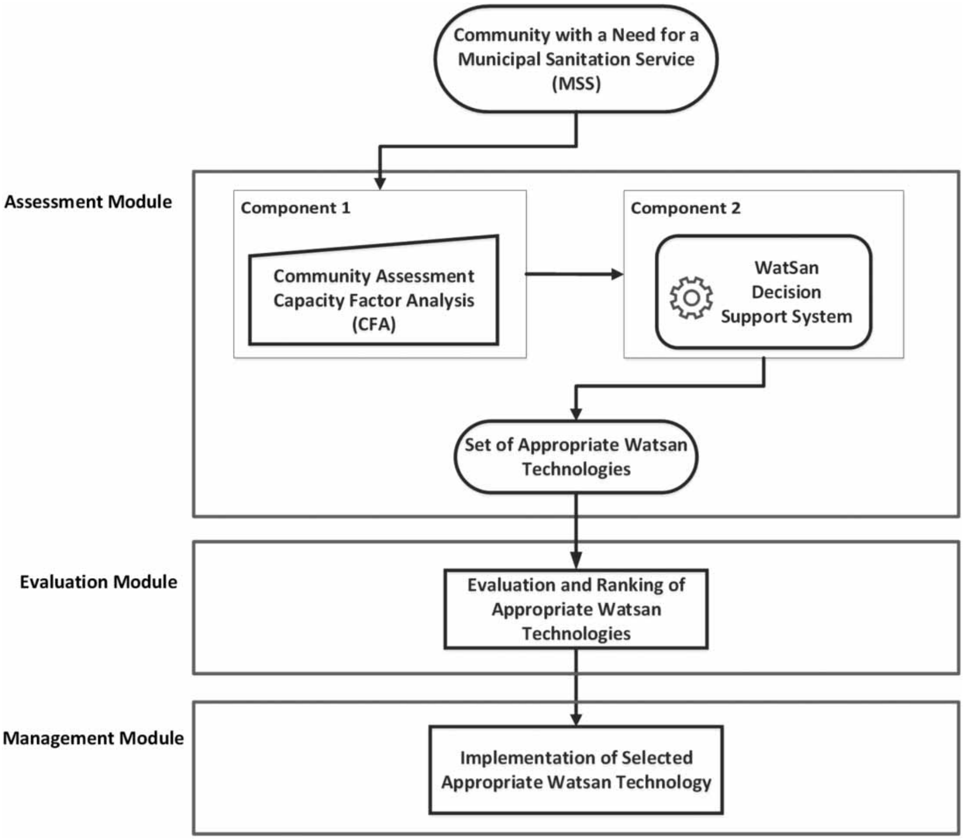


**Figure 1** | Decision model framework.

Evaluation, and Management. It allows water and sanitation professionals to select and implement appropriate technologies for water supply and sanitation infrastructure. Module one of the decision model consists of two components: the capacity factor analysis (CFA), which is used for the assessment of a community's capacity to manage a municipal sanitation service (MSS) (Bouabid & Louis 2015), and a decision support system (DSS), which is used to select appropriate technology options. In this research, the term MSS refers to any of the three basic sanitation services, namely drinking water supply (DWS), wastewater and sewage treatment (WST), or management of solid waste (MSW). Storm water management is commonly considered an MSS, especially in cities with combined sewer systems that mix storm water with sewage in the wastewater collection system. Storm water is excluded from the analysis at this stage of the research, and from this paper.

The purpose of this paper is to present the DSS, including the Assessment module, and to report on the evaluation of the DSS' performance in selecting appropriate water supply and sanitation (Watsan) technologies in simulations and in case study communities. In ongoing research to be published later, we will report on case studies in management that involve the implementation and viability of selected Watsan technologies.

## Component 1: capacity factor analysis (CFA)

Component 1 of the Assessment module of the DSS is the CFA model. It was developed by Bouabid & Louis (2015) to assess a community's capacity to manage and operate MSSs sustainably. The assessment of a community's capacity is based on eight capacity factors (CFs) that capture the community's capability to manage a given MSS sustainably. Guidelines for the assessment of the CFs were proposed for each one of the three MSSs: DWS, WST, and solid waste management. The CFs and its respective constituents are presented in Table 2.

**Table 2** | Community capacity factors for municipal sanitation services

| # | Capacity factors | Constituents |
|---|---|---|
| 1 | Institutional | Legislation (standards), Regulations, Administration, Governance |
| 2 | Human Resources | Professional, Skilled labor, Unskilled labor, Literacy rate |
| 3 | Technical | Operations, Maintenance, Adaptation, Supply chain (spare parts) |
| 4 | Economic | Private sector, Budget, User fees, Bond rating, Asset values |
| 5 | Energy | Primary source, Back up, budget dedicated to energy, power outage rate |
| 6 | Environment | Quality–sensitivity (footprint, carrying capacity), Quantity of resources |
| 7 | Social | Communities, Stability, Equity, Castes, Participation rate |
| 8 | Service | Quantity, Quality, Accessibility, Affordability, Reliability |

The result of the community's capacity assessment is defined by a metric, the community capacity level (CCL), using a 1–5 capacity level scale. The CCL summarizes the overall capacity of a community to operate and manage an MSS sustainably. Managing the system for an infrastructure service sustainably means that the community is able to sustain its access to the service at the designed level (quantity and quality) over the planning horizon for the system. A CCL score of 1 represents the lowest capacity, meaning that the community is only capable of managing the most rudimentary Watsan system, such as drinking water fetched by bucket from surface water or borehole, or an unventilated pit latrine. A score of 5 represents the highest capacity, meaning that the community is capable of managing the most advanced Watsan system, such as fully automated water treatment or SCADA-based wastewater treatment plant.

## Component 2: decision support system (DSS)

The second component of the Assessment module is the DSS. It consists of a user interface, a database of water supply and sanitation technologies, and data on developing communities that use them, as well as a matching algorithm for the selection of appropriate technology options for a given community profile. Figure 2 presents the framework of the DSS.

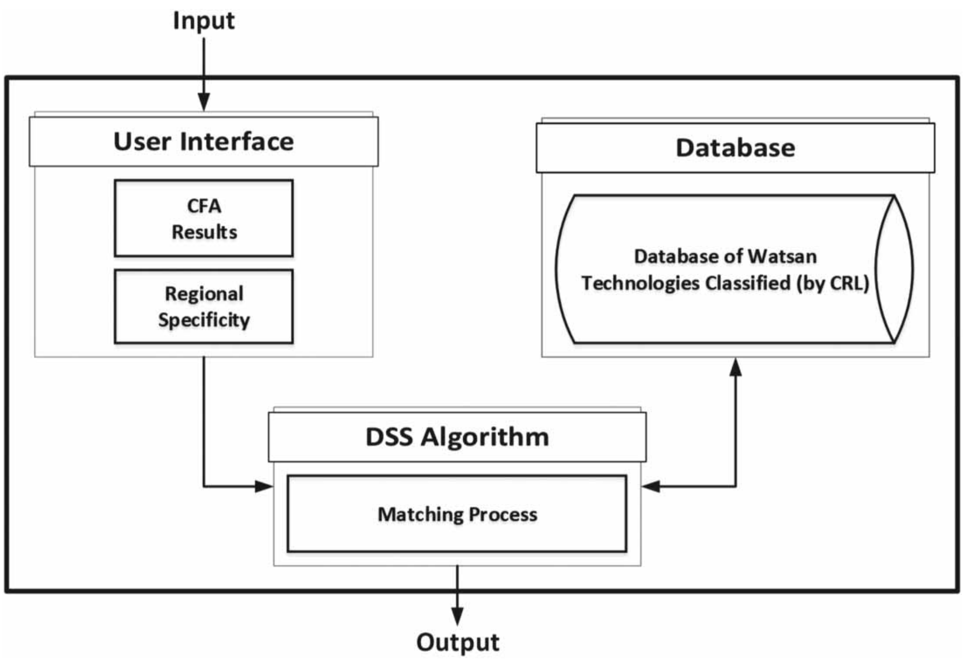


**Figure 2** | Decision support systems framework.

## User interface

The inputs to the DSS are done through a *User Interface*. The community assessment results from the CFA are used as inputs in the DSS *User Interface*. They consist of the scores of the assessment of seven of the CFs and the overall CCL. The 8th CF, the Service CF, is assessed but not used as input since it is the one that we wish to improve in the process. In the language of optimization, the 8th CF would be the objective function and the other seven CFs would be the constraints. The technology choices would be the decision variables. The other inputs in the DSS *User Interface* are the RS of the community. The latter represents the geographical location where the community is located and its settlement type (ST). These data would constitute the input variables in our optimization analogy.

## Database of the DSS

The database of the DSS is made of several tables. Three tables contain Watsan technology options for the three MSSs, namely DWS, WST, and MSW. First, the Watsan technologies are classified by the specific MSS they provide. Then, in each category, Watsan options are classified by the capacity requirement level (CRL) metric. The CRL metric defines the capacity level a community must have to operate and maintain a given Watsan technology sustainably. The classification of the technology options by CRL was achieved using a machine learning technique, 'support vector machines (SVMs)' model applied to classification problems (Bouabid & Louis 2018). In addition to the information on the Watsan technologies, the database contains information on developing communities that have implemented and are operating Watsan technologies sustainably. In this paper, we assume that a Watsan system is sustainable when it is operating and delivering its service for at least 2 years after it has been installed. The information on developing communities is defined by their profile, with the seven CFs and its related constituents, as well as its RS and the ST where the communities are located. The definition of these two characteristics is provided below.

The first criterion of the RS used in this DSS is the geographical location. It is based on the classification of the biogeographical provinces of the world as proposed by Udvardy (1975). This classification is based on eight biogeographical divisions of land and freshwater areas of the surface of the earth. These biogeographical divisions, called Realms, are the highest taxonomic groups of this classification and represent continents or subcontinent-sized areas with unifying features of geography and fauna. Table 3 presents the eight biogeographical realms with their corresponding numbers from 1 to 8.

For the database of the DSS, we used the entire set of realms in the *Regional Specificity table*. However, only six of the biogeographical realms, Palearctic, Africotropical, Indomalayan, Oceanian, Australian, and Neotropical, comprise most of the world's population with unmet demand for improved water supply and sanitation services. The biogeographical realms are subdivided into 14 major formation types or Biomes, which are presented in Table 4 with their respective descriptions. Finally, the last classification subcategory of the RS used by Udvardy (1975) is the Province. Each realm is comprised of several provinces, numbered consecutively. The representation of the biogeographical provinces of the world is shown in Figure 3. The classification of the RS identification code used in the DSS is similar to the one proposed by Udvardy (1975). It is defined by a sequence of six numbers, where the first two numbers are for the realm identification, the second two for the province, and the last two for the biome. The sequence is as follows: # # (Realm) – # # (Province) – # # (Biome).

For example, an area of South America in the *Neotropical* realm (realm 08), located in a province of *Llanos* (province 27), within the biome *Tropical Grasslands and*

**Table 3** | Biogeographical realms

| # | Biogeographical realms |
|---|---|
| 1 | Nearctic |
| 2 | Palearctic |
| 3 | Africotropical |
| 4 | Indomalayan |
| 5 | Oceanian |
| 6 | Australian |
| 7 | Antarctic |
| 8 | Neotropical |

**Table 4** | Classification of biomes types

| # | Biomes types |
|---|---|
| 1 | Tropical humid forests |
| 2 | Subtropical and temperate rain forests or woodlands |
| 3 | Temperate needle-leaf forests or woodlands |
| 4 | Tropical dry or deciduous forests (including monsoon forests) or woodlands |
| 5 | Temperate broad-leaf forests or woodlands, and subpolar deciduous thickets |
| 6 | Evergreen Sclerophyllous forests, scrubs, or woodlands |
| 7 | Warm deserts or semi-deserts |
| 8 | Cold-winter (continental) deserts and semi-deserts |
| 9 | Tundra communities and barren arctic deserts |
| 10 | Tropical grasslands and savannas |
| 11 | Temperate grasslands |
| 12 | Mixed mountain and highland systems with complex zonation |
| 13 | Mixed island systems |
| 14 | Lake systems |

*Savannas* (biome 10) will have the corresponding RS identification code: **08 – 27 – 10**.

The second criterion of the RS used in the DSS is the type of settlement of the community. We use three categories of settlement types to identify a developing community: urban settlement, peri-urban settlement, and rural settlement.

The classification of the ST is determined by several criteria. According to Dijkstra & Poelman (2014), there is no formal universal definition of urban areas that has been adopted by national governments or by the international community. The ST we use in the Watsan communities' data in the DSS is based on the definitions presented in Table 5.

Furthermore, the determination of the ST such as urban, peri-urban, and rural will be determined on a case-by-case basis drawing from the definitions of the settlement types by the host country for every developing community studied in terms of access to MSSs, we propose accepted definitions and differences between peri-urban and rural areas for the settlement types. Peri-urban areas are located between consolidated urban areas and rural areas. According to Barreto Dillon & Buzie (2008), the Peri-urban components for access to MSS are the following: 'more sanitation providers, more equipped in infrastructures, less space for construction, a higher opportunity for market development, and possible intervention of decentralized national water and sanitation services'. Rural areas are located outside towns

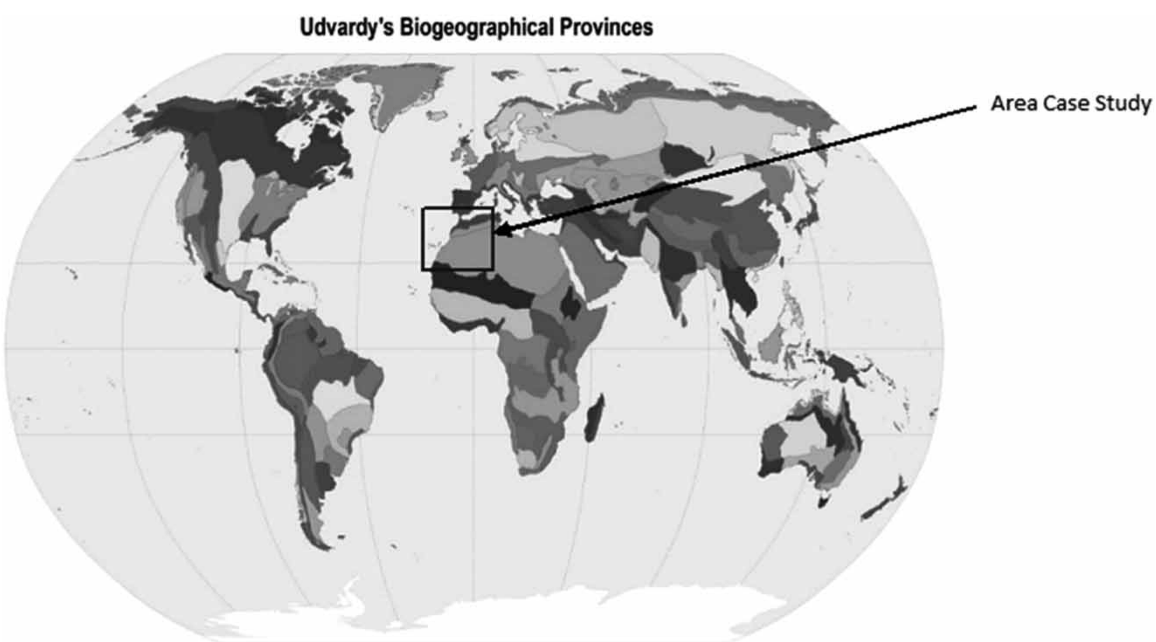


**Figure 3** | Classification of the biogeographical provinces of the world [8].

**Table 5** | Definitions settlement types

| **Area formality** **Density** | **Urban (1)** **Formal (1)** | **Informal (2)** | **Peri-Urban (2)** **Formal (1)** | **Informal (2)** | **Rural (3)** **Formal (1)** | **Informal (2)** |
|---|---|---|---|---|---|---|
| Low density (1) | Lots | Squatters | Lots | Squatters | Village | Squatters |
| High density (2) | Tenements | Ghetto | Tenements | Shanty town | Town | Shanty town |

and cities; they are characterized by low population densities and small size. Rural areas are also characterized by relatively lower access to infrastructure facilities such as markets, schools, and hospitals. In terms of access to MSS, and according to Barreto Dillon & Buzie (2008), the Rural components for access to MSS are 'poor infrastructures, no service providers, more space for construction, low population density, higher need for training, bigger potential for reuse of sanitation by-products, worse institutional representation'. Figure 4 illustrates the spatial distribution of the three main area types of human settlements. Ultimately, the ST is determined by the dominant characteristics of the service area in the judgment of the local planners and decision makers. This introduces significant subjectivity in this element of the DSS. Data from the case studies of ongoing research will address this limitation by means of machine learning algorithms.

In the DSS, we identify the RS' settlement type of a community with a sequence of the three digits, where the first one represents the area type, the second one the formality type, and the last one the type of density: # (Area) – # (Formality) – # (Density). For example, a community located in a peri-urban area, settled in a formal jurisdiction, and with a high population density will have the following number sequence for its ST in the database: **2 –1 – 2**.

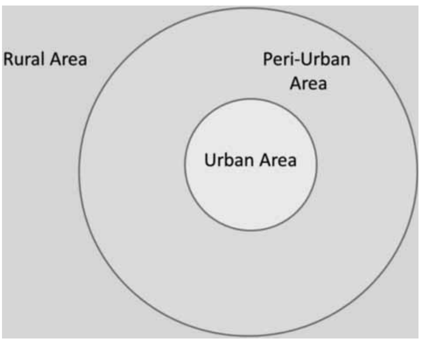


**Figure 4** | Settlement – area types.

## DSS algorithm

The third and last component of the DSS is the *Appropriate Matching* (AM) algorithm. The framework of the algorithm is presented in Figure 5.

First, the user will enter, through the *User Interface*, a given MSS need which could be DWS, WST, or MSW. The next input is the community's capacity assessment resulting from the CFA. It includes the CFs scores and the CCL score. Finally, the last input is the RS information of the developing community. The matching algorithm process starts with a selection from the database Watsan technology options that have a CRL metric consistent with the host

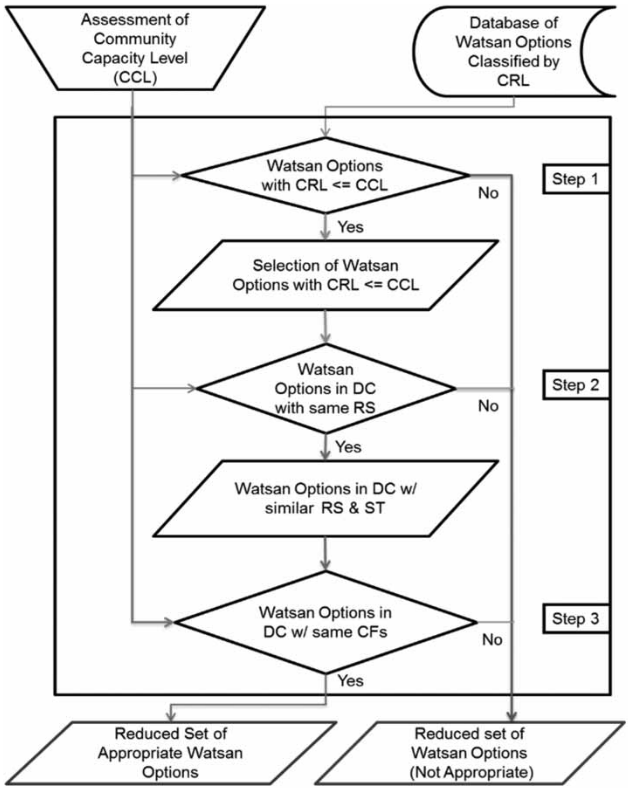


**Figure 5** | DSS matching algorithm.

community assessed CCL metric. This step ends with a selection of a subset of Watsan technology options that have a CRL ≤ CCL. This is a conservative selection approach meant to ensure that the community has the capacity to manage any of the technology options it selects from this set.

The next step in the DSS algorithm is the choice of a reduced subset of Watsan technology options from a shortlist produced by the CRL ≤ CCL test. In this stage, the tool examines the shortlist options to systems that have been implemented and operated sustainably in communities that are located with similar RS to the host community. The step ends with a further reduced subset of Watsan technology options with CRL ≤ CCL, and implemented and operated by communities with similar RS.

Finally, the last step of the DSS algorithm is the selection, from this last reduced subset, of a final set of Watsan technology options, that are operating sustainably by communities with a similar capacity profile as that of the host community. At this point, the DSS has done its job and the decision makers must obtain estimates of the cost, implementation time, operator training, and other criteria that must be traded off to make the final selection of the water or sanitation system for their community.

Based on the selection criteria proposed in the matching algorithm, we consider that the final set of Watsan technology options selected by the DSS are most likely to be appropriate technologies. Indeed, they require a technology level to operate that is met by the host communities, and they have been operated and maintained sustainably by communities with a similar profile and capacity level, and located in equivalent regions of the world and ST.

## BUILDING THE DSS

### Software

The first version of the DSS for the selection of appropriate Watsan technology options is developed with Microsoft Access software. At this stage of development, the DSS is not accessible online; however, it was designed with this feature in mind, and MS Access offers the capability for a web-based user interface. The entity-relationship diagram (ERD) retained for the design of the DSS database is presented in Figure 6.

The DSS database is structured with nine tables. The first table is the *Community Table*. It contains data on developing communities such as the name of the community, the country where it is located, the RS classification, and the ST identification. The *Community Table* also contains data on Watsan technology options implemented and operating in these developing communities. The second table of the DSS database contains data of the *Regional Specificity* classification, and the third table of the *Settlement Type* identification. The fourth, fifth, and sixth tables presented in the ERD of the DSS database contain developing communities' capacity factor assessments for the three MSS. These tables contain the CF scores and the corresponding CCLs scores from the respective assessments. These tables are labeled *Community CFA_DWS*, *Community CFA_WST*, and *Community CFA_MSW*. Finally, the last three tables presented in the DSS database ERD contain the inventory of Watsan technology options: one for the DWS options, one for the WST options, and one for the MSW options. In each one of the Watsan technologies tables, an instance or a technology option is identified with a unique identification number, a set of unit processes, and a CRL score.

### Appropriate Matching algorithm

The framework of the AM algorithm is presented in Figure 5. For a given community with a need for an MSS infrastructure, the DSS *User Interface* requires the inputs of the results of the CFA assessment with the following information: Community name, assessed CFs and CCL scores, and finally, the RS of the community. The AM algorithm uses the results of the assessment of the community's capacity level to operate and maintain a given MSS sustainably to proceed with the matching process. The AM process follows three steps as follows:

The first step of the matching process is done by selecting Watsan technology options that have a CRL metric equal to or lower than the assessed CCL metric of the host community. The AM algorithm selects a set of Watsan technology options with a CRL metric that is less than or equal to the CCL entered. The second step of the AM process is achieved with the selection, from the set of Watsan options

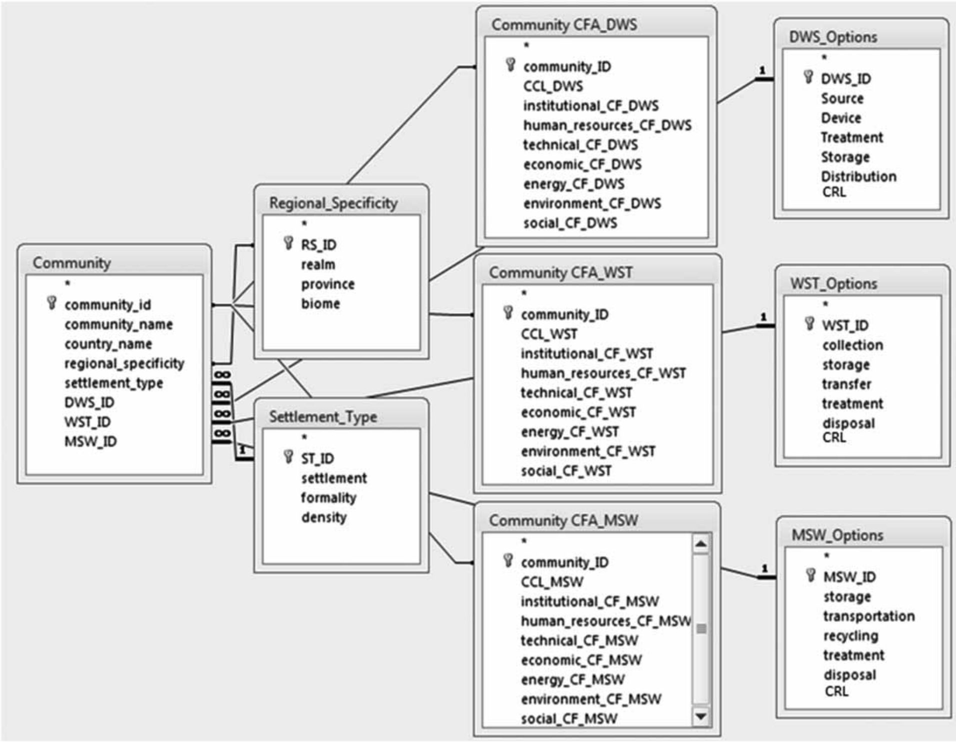


**Figure 6** | DSS – entity relations diagram.

obtained in the first step, of a subset of options that are implemented in communities with similar regional specificity and settlement type to the one of the host community. In this process, the matching parameters are the biome type of the *Regional specificity* (RS) of the community and the *Settlement type* (ST). The third and last step of the AM algorithm is completed with a selection from the reduced subset of remaining candidates of a final set of Watsan options that have been implemented and operated by communities that have a profile similar to the one of the host community. In this final step, the algorithm will compare the CFs of the host community to the CFs of communities operating Watsan options of the final subset. Only those Watsan options that have been implemented successfully in communities that have equal or lower CFs will be selected. In this last step of the AM process, the comparison of the CFs is performed using a 1–5 level scale instead of the initial 1–100 CF scoring scale. This more generalized scale provides more flexibility in the matching process without compromising the overall similarity of the capacities of the developing communities. For example, if the score of $CF_2$ of the host community is 34, this score corresponds to level 2 on the 1–5 scale. The level 2 of the 1–5 scale includes CF scores ranging between 21 and 40. Therefore, any community with a $CF_2$ score between 21 and 40 will have a similar $CF_2$ score as the host's $CF_2$ score. Table 6 presents the conversion between the CFs scores on the 1–100 scale and the 1–5 level scale (Bouabid 2013).

## TESTING AND RESULTS

### DSS testing

The evaluation of the performance of the DSS was conducted initially for the DWS module. Two evaluations of

**Table 6** | Correspondence between CF scores and the 1–5 level scale

| CF scores | 1–20 | 21–40 | 41–60 | 61–80 | 81–100 |
|---|---|---|---|---|---|
| Scale level (1–5) | 1 | 2 | 3 | 4 | 5 |

the DSS were done. The first evaluation was done with data collected from field research in Morocco to validate the selection done by the AM algorithm. The second evaluation was done by means of simulation. It was completed with generated data of developing communities to test the overall functionality of the DSS.

## Validation of the DSS selection algorithm

This evaluation aims to test the selection of DWS options performed by the AM algorithm. The validation of the performance of the DSS algorithm is done by making sure that the recommendation of the DSS corresponded to the DWS technology options implemented case study developing communities. The developing communities used in the evaluation were located in Morocco, and the data collection was conducted thanks to the assistance of the Moroccan Social Development Agency (ADS). Since it started its activity in 2000, the ADS has funded hundreds of development projects in Morocco. The villages and small towns used in the testbed of the DSS were selected from communities that received funding from the ADS for their DWS infrastructure. The criteria used to select the developing communities is that the installed DWS options have been operating sustainably for at least 2 years after their implementation. We used six developing communities for this evaluation. The data collected included the CFs of the community, the RS and ST, and the DWS options implemented. As we can see in Figure 7, Morocco is part of the Palearctic realm (02) and has three biogeographical provinces.

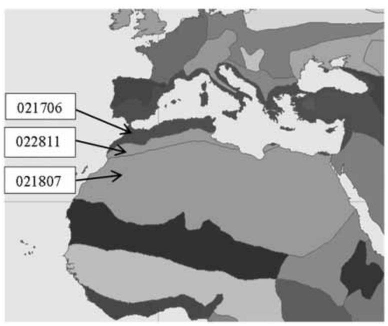


**Figure 7** | Case study – regional specificity of Morocco's provinces.

Each province presents features related to different biomes. In the North, we find the *Mediterranean Sclerophyllous* province (17), with a biome type *Woodland/Scrubland* (06), and the RS identification is 021706. In the Center, we find the *Atlas Steppe* province (28), with a biome type *Temperate Grassland* (11), and the corresponding RS identification is 022811. Finally, and in the South, we find the *Sahara* province (18), with a biome type *Subtropical Desert* (07), and the RS identification 021807. Table 7 summarizes the data related to the developing communities used for the validation test of the DSS.

For each developing community used for the validation test, we used the CFA to assess the community's capacity. The guidelines of the CFA for DWS were used, and the results of the assessment for the six developing communities are presented in Table 8. These scores are entered into the DSS through its *User Interface* along with the regional specificities and settlement types of the developing communities. The results of the DSS validation testing led to the following results.

For the four communities, Khabach, Ait BouAhmed, Taschert, and Ait Said, the assessment of the CFs led to a CCL metric score of 3 for all except for Ait Said community, for which the CCL score was 2. The score of 2 for Ait Said results from its score of 31 on the CFA assessment of its Human Resources Capacity. This score is in the 21–40 range, which converts to a score of '2' on the CCL scale. It is noteworthy to mention here that the overall CFA for a community is set to the lowest score earned by any of the seven CFs used for making the final assessment. This is another conservative element of the selection process as it forces the CCL to the lowest value, again trying to assure that the community will have the capacity to manage technologies selected based on their weakest CF. In the decision process, the DSS matching algorithm went through all the selection criteria successfully and retrieved from the database DWS options that match the characteristics of the host community: with a CRL $\leq$ CCL, operating sustainably by communities located in similar RS (geographical and settlement) to the one of the host community, and that have the same capacity profile. In the case of our validation test, the DSS report provided a list of DWS technology options among which were the ones that were operated by the communities used in the testbed. This test confirmed that the DSS recommended the same

**Table 7** | DSS validation test – developing communities data

| ID | Country | County | Community | Population | RS_ID | ST_ID | DWS_ID |
|---|---|---|---|---|---|---|---|
| 8 | Morocco | Boulemane | Ait Khabach | 840 | 021706 | 311 | 344 |
| 7 | Morocco | Boulemane | Chbite | 190 | 021706 | 311 | 584 |
| 9 | Morocco | Haouz | Ait Bou Ahmed | 800 | 022811 | 311 | 232 |
| 11 | Morocco | Haouz | Ait Said | 330 | 022811 | 311 | 96 |
| 10 | Morocco | Haouz | Ait Taschert | 840 | 022811 | 311 | 228 |
| 6 | Morocco | Sidi Kacem | Lemlaqite | 1,300 | 021706 | 311 | 222 |

**Table 8** | DSS validation test – CFA assessment scores for the developing communities

| Communities | Institutional | Human resources | Technical | Economic | Energy | Environment | Social |
|---|---|---|---|---|---|---|---|
| Ait Khabach | 43 | 41 | 43 | 41 | 46 | 53 | 46 |
| Chbite | 37 | 31 | 39 | 30 | 48 | 48 | 49 |
| Ait BouAhmed | 42 | 41 | 43 | 43 | 41 | 48 | 61 |
| Ait Said | 42 | 31 | 43 | 35 | 41 | 45 | 52 |
| Ait Taschert | 46 | 41 | 46 | 42 | 43 | 55 | 61 |
| Lemlaqite | 43 | 33 | 36 | 33 | 46 | 45 | 59 |

DWS options that the communities have implemented and operated sustainably. Thus, for this limited test, the DSS performed successfully.

In the case of the town of Lemlaqite and the village of Chbite, the assessment of the CFs led to a CCL metric score of 2 in both cases. However, the two communities have implemented DWS options that have a CRL of 4 and 3, respectively. When we used the DSS to test the selection process of a DWS option for each community, obviously the results are not in line with the DWS options installed by the communities because the options have a CRL metric higher than the CCL metric. In other words, the DSS algorithm selects only DWS options that have a CRL less than or equal to the assessed CCL of the community. In these cases, the model provides a warning that the installed technologies might not be sustainable if the host community could not develop its lowest scored CFs.

## DSS simulation

The second test for the evaluation of the performance of the DSS was conducted through simulation. This virtual evaluation was done for the DWS module of the DSS. We used some synthetic data on developing communities that we generated. The data used in the simulation correspond to a developing community living in a location with an RS defined by a biome type *temperate_grassland (11)*, which corresponds to an RS identification: *028211*. The community is located in a rural area, in a formal and low-density ST. The corresponding identification of the ST is *311*. The data related to the community are then entered into the *User Interface* of the DSS; it includes the RS and ST of the community, as well as its simulated CFs scores and corresponding CCL metric.

The search is initiated, and the results are then delivered in a report that presents a set of appropriate DWS options selected through the matching process. The '*Appropriate DWS Options*' report generated by the simulation is the output of the DSS. In this simulation, it contains only two appropriate DWS options: DWS_ID 232 and DWS_ID 228. Each DWS option is defined by five unit processes: source, device, storage, treatment, and distribution. The DWS option selected by the DSS and its specifications are presented in Figure 8.

In this simulation, the number of DWS options provided by the DSS report is small because the database of the DSS contains a small number of data on developing

Watsan Decision Support System
Report: Appropriate DWS Options

Community Name: simulation#2

| DWS_ID | Source | Device | Treatment | Storage | Distribution | CRL |
|---|---|---|---|---|---|---|
| 232 | drilled_well | submersible_pump | domestic_chlorinatio | elevated_reservoir | domestic_connectior | 3 |
| 228 | drilled_well | submersible_pump | chlorination_in_pipec | reinforced_concret | domestic_connectior | 3 |

**Figure 8** | DSS – simulation results.

communities. Indeed, at the current stage of development of the DSS, there are not ample data in the '*Community*' table of the DSS database, and therefore, the resulting selection is limited. This will improve as more case studies are added to the DSS database through further data collection.

### Discussion

At this stage of the development of the DSS, more data of developing communities need to be collected and entered into the DSS database to validate its preliminary results and increase its robustness. Indeed, the more data we collect and enter into the database of the DSS, the more efficient the matching algorithm will be. This is one of the limitations of this decision tool, because its selection algorithm is based on, among other criteria, developing communities that have operated DWS options sustainably. It is also one of its strengths since the selection process is based on previous water supply and sanitation infrastructure that has been installed successfully in developing communities with similar profiles and located in similar geographical regions.

## CONCLUSION

The goal of this research is to provide water supply and sanitation practitioners and international aid organizations with a DSS that will allow them to choose, among the numerous available options, the most appropriate systems for securing sustained access to safe drinking water and improved sanitation. In developing the decision model proposed in this research, we have tried to fill the gaps identified by Palaniappan *et al.* (2008) in the existing Watsan decision tools.

The social factor, missing in most of the existing decision tool, was incorporated in our proposed model. More specifically, it is included in the CFA assessment tool, where we assess the social and cultural capacity factor of the developing communities and is used as input through the DSS *User Interface*.

The second missing element, the RS, is included in the DSS algorithm. It is used to select Watsan technologies that have been operating successfully by communities located in a similar geographical region and ST.

The third missing element, project replicability, is also addressed in our proposed decision model. It is a very important aspect of the design of the DSS, where the appropriate technology selection is based on previous successful technology implementation by similar developing communities. Though this does not guarantee that the Watsan technology selected by this DSS will succeed in providing sustained access to service in the host community, it uses an objective process to increase the likelihood of success over existing, heuristic methods.

Finally, the last missing element, a user interface, is integrated into our proposed decision tool in the DSS *User Interface* itself. This last element requires additional development as we plan to make it web-based so that it can be easily accessed online by users.

The evaluation of the proposed DSS shows that its overall performance is as expected. In the simulation used for the evaluation, the data entered corresponded to developing communities located in biome types, and profiles similar to the ones of some communities whose data are in the *Community* table of the Watsan DSS. The DSS delivered a few appropriate DWS options in the simulation due to the small number of data on developing communities currently in the database. Indeed, the Watsan DSS will achieve its full potential when a larger database is developed, with data on developing communities operating Watsan options in diverse geographic areas of the world. Watsan DSS can be a very useful tool in assisting Watsan practitioners and international aid organizations in the selection of appropriate

Watsan technology options. Data collection on developing communities and the Watsan technologies they operate will be conducted in future research, and a web-based interface of the DSS will be developed.

## DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (https://data.mendeley.com/datasets/2szmr4tg3z/2).

## REFERENCES

Banks, B. & Furey, S. 2016 What's working, where, and for how long. A 2016 water point update to the RWSN. In *7th RWSN Forum No. 4*. https://doi.org/10.1021/es402086n.Fisher.

Barreto Dillon, L. & Buzie, C. 2008 *NETSSAF Participatory Planning Approach. A Guideline for Sustainable Sanitation Planning*. Available from: https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/1344?pgrid=1.

Bouabid, A. 2013 *A Systems Approach for the Selection of Appropriate Water Supply and Sanitation Infrastructure in Developing Communities*. Available from: https://libraetd.lib.virginia.edu/public_view/ht24wj630.

Bouabid, A. & Louis, G. 2015 Capacity factor analysis for evaluating water and sanitation infrastructure choices for developing communities. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2015.07.012.

Bouabid, A. & Louis, G. 2018 Classification of water supply and sanitation technology options using machine learning methods. In *INCOSE-EMEA Sector Conference*, Berlin, Germany.

Dijkstra, L. & Poelman, H. 2014 *A Harmonised Definition of Cities and Rural Areas: The New Degree of Urbanisation*. Available from: https://ec.europa.eu/regional_policy/sources/docgener/work/2014_01_new_urban.pdf.

Palaniappan, M., Lang, M. & Gleick, P. H. 2008 *A Review of Decision-Making Support Tools in the Water, Sanitation, and Hygiene Sector*. Pacific Institute. Available from: https://pacinst.org/wp-content/uploads/2013/02/WASH_decisionmaking_tools3.pdf.

Roser, M. 2020 *Future Population Growth*. Available from: https://ourworldindata.org/future-population-growth#citation (accessed May 5, 2020).

Udvardy, M. D. F. 1975 A classification of the biogeographical provinces of the world. In *IUCN Occasional Paper, International Union for Conservation of Nature and Natural Resources*. No. 8. cabi:19780643110.

UNESCO 2019 *World Water Development Report 2019 - Leaving No One Behind*. Available from: https://en.unesco.org/themes/water-security/wwap/wwdr/2019.

United Nations, General Assembly 2010 *The Human Right to Water and Sanitation*. A/RES/64/292. Available from: https://undocs.org/en/A/RES/64/292.

United Nations, GA 2015 *Transforming Our World: The 2030 Agenda for Sustainable Development – RES/70/1*. Available from: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

WHO/UNICEF 2017 *Progress on Drinking Water, Sanitation and Hygiene*. Available from: https://apps.who.int/iris/bitstream/handle/10665/258617/9789241512893-eng.pdf?sequence=1.

First received 5 October 2020; accepted in revised form 14 December 2020. Available online 28 January 2021