A new approach to implementing decentralized wastewater treatment concepts

Manfred van Afferden, Jaime A. Cardona, Mi-Yong Lee, Ali Subah and Roland A. Müller

ABSTRACT

Planners and decision-makers in the wastewater sector are often confronted with the problem of identifying adequate development strategies and most suitable finance schemes for decentralized wastewater infrastructure. This paper research has focused on providing an approach in support of such decision-making. It is based on basic principles that stand for an integrated perspective towards sustainable wastewater management. We operationalize these principles by means of a geographic information system (GIS)-based approach 'Assessment of Local Lowest-Cost Wastewater Solutions' – ALLOWS. The main product of ALLOWS is the identification of cost-effective local wastewater management solutions for any given demographic and physical context. By using universally available input data the tool allows decision-makers to compare different wastewater solutions for any given wastewater situation. This paper introduces the ALLOWS-GIS tool. Its application and functionality are illustrated by assessing different wastewater solutions for two neighboring communities in rural Jordan.

Key words | centralized management of decentralized wastewater clusters, GIS-analysis, implementation research, investment strategies for decentralized wastewater treatment

Manfred van Afferden
Jaime A. Cardona
Roland A. Müller (corresponding author)
Helmholtz Centre for Environmental Research – UFZ,
Permoserstrasse 15, 04318 Leipzig,
Germany
E-mail: *roland.mueller@ufz.de*

Jaime A. Cardona
BDZ-Training and Demonstration Centre for Decentralised Sewage Treatment,
An der Luppe 2, 04178 Leipzig,
Germany

Mi-Yong Lee
Helmholtz Centre for Environmental Research,
Office of the National Implementation Committee for Effective Decentralized Wastewater Management in Jordan, at the Ministry of Water and Irrigation,
Salem Al Hindawi St 45, 11183 Amman,
Jordan

Ali Subah
Ministry of Water and Irrigation,
Salem Al Hindawi St 45, 11183 Amman,
Jordan

INTRODUCTION

In general, decentralized wastewater management (DWWM) is defined as the collection, treatment, and reuse or disposal of wastewater at or near its point of generation (Crites & Tchobanoglous 1998). During the last decade, numerous small wastewater treatment technologies have been developed and evaluated by Wilderer & Schreff (2000), Bieker *et al.* (2010), Molinos-Senante *et al.* (2012), and Nivala *et al.* (2013). Along the way, the literature discussed the maximum size of 'decentralized wastewater systems' inconsistently. According to CEN (2005), small wastewater treatment systems are defined as serving less than 50 person equivalents (PE). The European Commission (EC 2001) and Ho (2005) defined decentralized wastewater treatment technologies as serving less than 5,000 PE, whereas Gutterer *et al.* (2009) and Wendland & Albold (2010) defined this threshold at wastewater flows of 1,000 m^3 per day or 10,000 PE respectively.

We suggest using the term 'decentralized' in a more pragmatic manner since decentralized systems complement, rather than compete with centralized wastewater treatment plants (WWTPs). Both concepts should be considered in identifying the optimal solution for any given sanitation problem. We use the term 'DWWM systems' for solutions at or near the point of wastewater generation that may include different plant sizes and treatment technologies, such as on-site treatment plants for individual homes, plants serving small to middle-sized clusters of homes or even entire communities. Many DWWM systems consist of multiple WWTPs serving the population of a defined area (Libralato *et al.* 2012).

In recent years, expert discussion has focused on the analysis of centralized versus decentralized wastewater management, pointing out the advantages and disadvantages of both approaches. In the discussion on potential application fields (Tchobanoglous *et al.* 2004; Lamichhane 2007; Orth 2007; Weber *et al.* 2007) and economics of DWWM systems (Engin & Demir 2006; Brunner & Starkl 2012), a special emphasis was given to the following:

- Conurbations that are growing quickly where decentralized systems allow for highly flexible solutions that can grow alongside changing conditions.

doi: 10.2166/wst.2015.393

- Rural and suburban areas, where costs for long-distance sewerage to centralized treatment are prohibitively expensive.
- Challenging topographical conditions that require pumping stations for central solutions.
- Investment costs and operation and maintenance requirements due to economies of scale.

Rather than deciding between a decentralized or centralized approach, we suggest evaluating a variety of alternative wastewater collection, treatment and disposal solutions as regards to their suitability and cost-effectiveness for the given local wastewater situation and its site-specific characteristics.

GIS-BASED ASSESSMENT

The ALLOWS (Assessment of Local Lowest-Cost Wastewater Solutions) geographic information system (GIS)-based assessment involves a geo-database, fed with geographical, spatial, socio-economic, and statistical data of the area of interest. This geo-database contains satellite imaging to determine the area's physical infrastructure, the number of residents per building, land use data to identify reuse options, potential plots for WWTPs (e.g. undeveloped municipal land), topographical conditions, gravity flow information through combination of the geo-database with digital elevation models, land ownership (e.g. parcel index), and international and national benchmark prices for all cost items (treatment technology, reuse infrastructure, network construction, pump and lifting stations, operation and maintenance labor, electricity and water, etc.).

ALLOWS generates financial indicators for different wastewater scenarios and thus enables planners and decision-makers to perform a comparative analysis to identify best solutions for the wastewater management problem at hand. Main factors that are required for finding sustainable solutions to wastewater problems are integrated in the analysis. These are: current and projected long-term demographic developments, connection degree, groundwater status and vulnerability to pollution from domestic wastewater, local reuse options (land use), potential treatment technologies based on local wastewater quantity and quality, existing infrastructures (sewage networks, centralized treatment plants, cesspools/septic tanks) and geographical conditions (topography, natural drainage) (Figure 1). With these factors different decentralized scenarios are developed, monetized and compared to the cost of a centralized solution.

The ALLOWS scenarios are built based on the following operations:

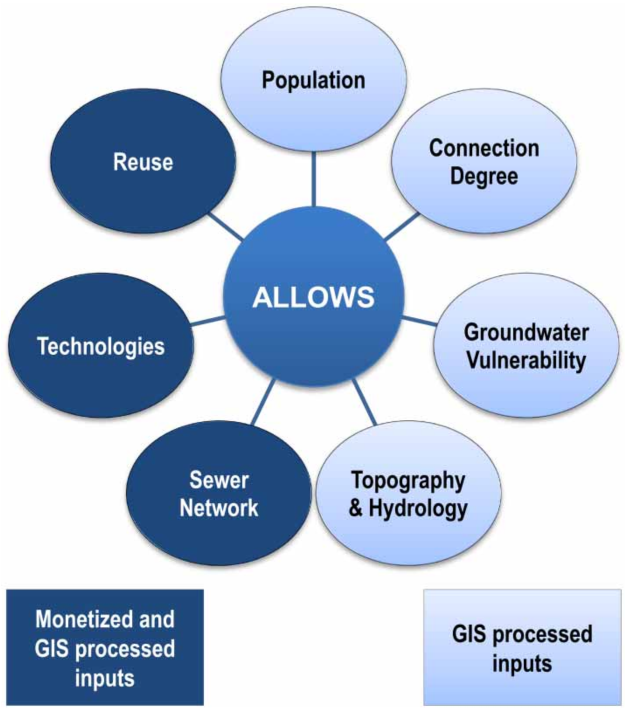

Figure 1 | ALLOWS input data.

- Estimating the required treatment capacity (m^3/d) for decentralized wastewater solutions using population statistics and data on land ownership to project housing development.
- Identifying micro-catchments on settlement scale that allow for wastewater conveyance without or with minimal pumping (gravity flow sewer networks).
- Designing spatial infrastructure clusters for DWWM scenarios.
- Estimating costs of construction, operation and maintenance (O&M) and reinvestments for different DWWM scenarios.
- Generating annualized cost for each scenario and determining their cost-efficiency by means of comparison among different scenarios.
- Optimizing cluster sizes to minimize O&M cost of DWWM systems.

Application example of ALLOWS in Jordan

To substantiate the practical relevance of ALLOWS as a decision-support tool and at solving actual wastewater problems, its application is shown here by the example of generating a solution for a local wastewater problem in Jordan. In Jordan and other water-scarce countries, wastewater treatment and reuse are vital components of alleviating the physical, social and economic pressures resulting from water scarcity (van Afferden *et al.* 2010). Jordan's 29 WWTPs presently serve about 68% of households, and capture and treat around 118 million cubic meters (MCM) of sewage per year, of which nearly 90% are blended with freshwater and reused in agriculture. But Jordan's potential for reuse has not yet been fully exploited. As stated in *Jordan's Water Strategy 2009–2022* the country aims to reuse 200 MCM of treated wastewater by 2022 (MWI 2009) and defines DWWM as a measure not only to alleviate Jordan's growing water scarcity but also to protect its main drinking water resource, its groundwater aquifers, from sewage pollution of unconnected settlements. From a wastewater management perspective Jordan is challenging as it features highly variable landforms (topography), dispersed settlement structures in suburban and rural areas, a strong long-term demographic growth, and highly vulnerable groundwater impacting fundamentally Jordan's drinking water supplies.

Since Jordan is a developing country, its infrastructure development depends mainly on financial assistance provided by development and donor agencies. Due to the comparatively smaller financial scopes of DWWM systems and the efforts involved for managing such small-scale investments, associated projects are currently not a priority for donor agencies. In the absence of economies of scale, uncertainty of cost recovery of O&M for public infrastructure is also a barrier.

To overcome these barriers, a critical mass of investment is required that renders possible the sourcing of financial donor support and cost-efficient O&M. We suggest defining clusters, e.g. a number of neighbouring DWWM systems that are financed and operated conjointly (van Afferden & Müller 2011).

Results of applying ALLOWS to the case of Ira and Yarqa in rural Jordan

In the following, ALLOWS is applied to generate solutions for an actual wastewater problem in Jordan. The assessment was conducted for Wadi Shueib, in Jordan. The wadi is located in the governorates of Amman and Al-Balqa. It comprises a total of 185 km^2 and includes the suburban areas of the municipality of Al-Salt, and a number of sub-districts including Ira and Yarqa, which are predominantly of rural character.

Wastewater situation in Ira and Yarqa

Ira and Yarqa, two neighboring villages in Wadi Shueib, are not connected to sewerage and are thus representative for rural settlements in Jordan. The predominant wastewater disposal infrastructure consists of cesspits at household level. The villages feature a significant population growth and major deterioration of groundwater quality mainly from infiltration of domestic wastewater from leaky cesspits.

ALLOWS inputs and development of geo-database

The ALLOWS input data (see Figure 1) have been collected and processed as follows.

Population and connection degree

For the selected area Ira–Yarqa (20 km^2) a population analysis was undertaken based on interpretation of GeoEye satellite imagery captured in April 2011. As a result, 1,710 buildings were identified, equivalent to 10,218 people, assuming an equivalent dwelling unit of six people per building. Using the projection for Al-Balqa governorate according to the Jordanian Department of Statistics, the population after 30 years was generated and the associated wastewater flow was determined to be 1,103 m^3/d assuming a per capita wastewater production of 74 l/d. The households of Ira and Yarka are currently not connected to a public sewer. Wastewater of each house is collected and infiltrated by backyard septic tanks.

Groundwater vulnerability

Werz & Hoetzl (2007) developed a groundwater vulnerability map for Wadi Shueib, based on geological and land use data. This information was combined with the connection degree map and digitalized. The analysis of Wadi Shueib shows that most areas that are not connected to sewerage are located in zones with a high or extreme groundwater vulnerability, indicating that an improvement of wastewater infrastructure would significantly reduce groundwater pollution.

Topography and hydrology

Based on interpretation of the digital elevation model and topography maps in ArcGIS (ArcHydro tool box), micro-catchment areas were identified in order to determine flow directions for design of the collection system. Additionally, the natural drainage streams were delineated and final catchment points defined. As a result nine micro-catchment areas were identified that include a total of 2,743 buildings.

Sewer network

It is the goal of DWWM scenarios to allow for the conveyance of wastewater by natural gravity flow wherever and whenever possible so as to avoid pumping. Thus, within the catchment areas, sewer lines and manholes were projected in ArcGIS based on local-level layers of buildings and streets. The estimated total network length and the number of manholes were used to generate cost estimates.

Technologies

Two technologies were chosen: (a) sequencing batch reactor (SBR) and (b) vertical flow constructed wetland (VFCW). Both are established treatment methods for DWWM systems all over the world.

(a) Since the required construction area is limited within settlements, compact technologies with a small footprint such as the SBR technology represent a suitable option. For the design of the SBR plants, German standards (DWA 2009) were applied. The excess sludge storage was designed to cope with at least 2 months of storage. In the cost calculation it is assumed that all SBR reactors are covered, thus avoiding evaporation. The raw wastewater chemical oxygen demand concentration was assumed to be around 1,000 mg/l. The dimensioning of the SBR systems for 50, 500, and 5,000 PE was provided in 2009/2010 by the German SBR supplier ATB.

(b) Advantages of VFCW include low O&M cost and very low energy demand (preliminary designs of VFCW for 50, 500 and 5,000 PE were made by UFZ in 2009). For VFCW systems bigger than 500 PE, an upflow sludge blanket reactor as primary treatment step was added. This combination is excellent for Jordanian conditions where high levels of biochemical oxygen demand prevail (Elmitwalli *et al.* 2003).

The performance of both technologies was defined to fulfill Class A of the Jordanian standard for reclaimed domestic wastewater (JS 893: 2006). This effluent quality is required for urban areas where potential human contact with treated wastewater should be restricted. Since the limit concentrations of JS 893: 2006, especially for nitrate (30 mg/l) and *Escherichia coli* (100 MPN/100 ml), are very low, a tertiary treatment step and disinfection complement the biological treatment.

For both technologies, design, construction and O&M cost were ascertained for the 50, 500 and 5,000 PE capacities based on local wastewater quantities and qualities and flow patterns. The cost components include pre-treatment, primary treatment, secondary (biological) treatment, denitrification, UV disinfection and sludge drying (cost estimation for sludge drying was only conducted for units of 500 and 5,000 PE).

Reuse

In order to identify suitable areas for reuse of treated wastewater, the land use of each catchment area was ascertained. Areas for irrigation accumulating to a total of 4.5 km^2 within the perimeters of both settlements were identified. The total potential for reuse was calculated to be 371,587 m^3/year.

ALLOWS wastewater scenarios for Ira and Yarqa

ALLOWS enables the defining of different scenarios by means of variation in the design and type of sewer network well as the design, type, size and locations of WWTPs. In this particular case four scenarios were developed, one scenario for connection to a central WWTP (scenario I) and three DWWM scenarios (scenarios II–IV). For each scenario minimum infrastructure requirements were generated using, for example, natural gravity flow in order to minimize pumping requirements.

Scenario I

For Ira and Yarqa one wastewater management scenario was defined involving a central WWTP that would serve both villages (Figure 2(b)). In this scenario wastewater is collected and transported to the nearest existing central WWTP using trunk lines and lift stations. For this study, in order to estimate construction and O&M cost of centralized treatment the historical costs of activated sludge treatment plants were applied. Furthermore, it is assumed that all infrastructures in this scenario, i.e. WWTPs, lift stations and trunk lines, are operated and maintained by Jordan's public water authority, the Water Authority of Jordan (WAJ).

The scenarios for DWWM are based on a cluster of nine different decentralized WWTPs and nine corresponding gravity sewer networks (Figure 2(a)). Since O&M is essential for cost-efficiency and sustainability of any wastewater disposal system three sub-scenarios including respective O&M schemes were defined.

WAJ is generally responsible for all water services in Jordan but can, in principle, assign this duty to a private entity. Several service companies exist in Jordan that operate, maintain and monitor water supply, central water and

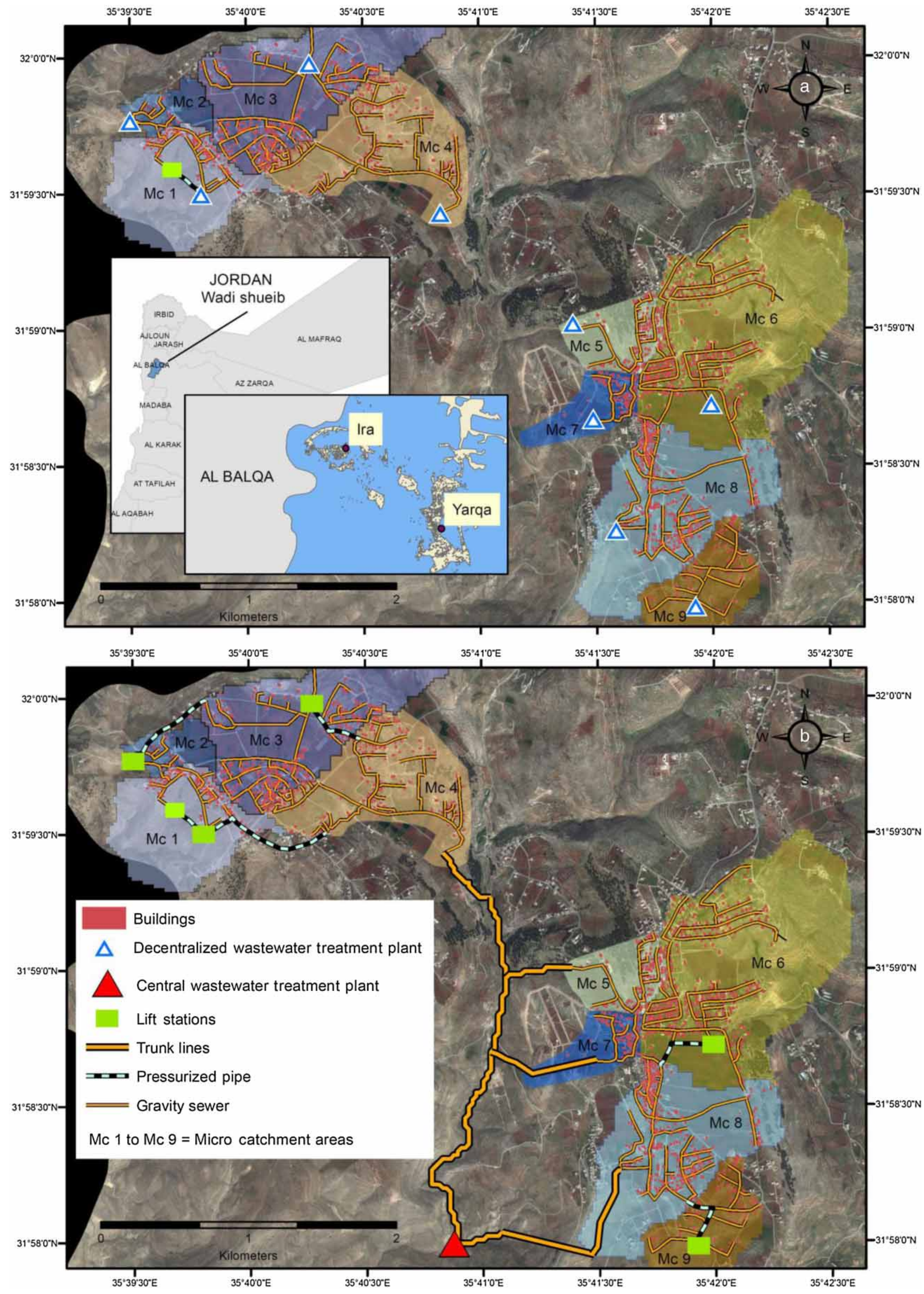

Figure 2 | Decentralized (a) and central (b) wastewater treatment scenario for Ira and Yarqa.

WWTPs, and collection systems. However, there exists no experience to date of DWWM systems.

Scenario II

Cluster of decentralized WWTPs with private sector participation. In this scenario a private entity will be in charge of O&M, while the sewer network will be maintained by WAJ.

Scenario III

Cluster of decentralized WWTPs operated by the public sector. In this scenario the WWTPs as well as the sewer networks will be operated by WAJ. A private entity will be in charge of O&M for the WWTPs.

Scenario IV

Cluster of decentralized WWTPs with reuse benefits. This scenario was generated based on scenario III including reuse benefits from selling treated wastewater to local farmers at market price.

Cost analysis

As a main output, ALLOWS develops a comparative cost assessment of different local treatment and reuse solutions, each represented by one scenario. Relevant criteria for the financial assessment are the total cost incurred during the complete life cycle of the project. Usually, wastewater infrastructure projects assume 25 years for WWTPs and 50 years for collection systems (DWA 2012). Within a project period different costs occur and it is essential that a robust cost estimate is conducted to provide appropriate financial data.

For this reason, ALLOWS scenarios were compared using the total project value (TPV) method elaborated by the DWA guideline for costs comparison of wastewater infrastructure projects (DWA 2012). Scenarios I to IV were compared in terms of TPV and specific treatment costs (STC) calculated in Jordanian dinar per cubic meter of treated wastewater (JOD/m^3). Additionally, a cost comparison between the TPV of the decentralized solutions and the TPV of connecting the communities to a centralized WWTP was carried out in order to reveal the economic competiveness of the decentralized solutions versus a centralized approach. In applying the TPV method to ALLOWS scenario analysis the following cost components were calculated: total capital cost (TCC), reinvestment cost (RIC), O&M cost (O&MC). A discount rate of 3 and 5% and a 30-year project period was assumed in order to determine the total financial scope of each solution for different macroeconomic conditions.

Scenarios I–IV were compared in terms of TPV and STC calculated in JOD/m^3. Additionally, a cost comparison between the TPV of the DWWM solutions and the TPV of the centralized solution was carried out in order to assess whether the decentralized scenarios are competitive.

TCC represents all infrastructure components required to build a treatment system. This involves mechanical and electrical components of a WWTP and the associated civil work. For TCC estimation a database generated from local unit prices for components such as excavation, labor, pipes, pumps and cabling was obtained through interviews with Jordanian companies and surveys of local market prices. Since the Jordanian currency is in practice pegged to the US dollar, historical costs were converted to present values, by using the urban consumables index of the US Department of Labor (US-BLS 2012). Present values for historical costs were updated using the equation presented by Friedler & Pisanty (2006). Expenses that are not directly associated with the construction of WWTPs were included as 'other cost' and cover land acquisition costs, cost for construction of administrative buildings, engineering design cost, overheads, profits and contingencies.

For each technology a specific cost function was developed. Cost functions allow modeling of different possible WWTP capacities and are widely used to estimate cost of wastewater infrastructure (Tsagarakis *et al.* 2003; Friedler & Pisanty 2006; Nogueira *et al.* 2007).

O&MC for decentralized scenarios includes cost for personnel, energy consumed by electrical devices (pumps, aerators, ultraviolet lamps), and laboratory analysis as well as sludge treatment. All personnel cost were calculated in JOD/month. O&MC cost was calculated based on actual (2011/2012) Jordanian salaries and current energy prices in Jordan (JOD0.05/kWh). In addition, spare parts were included assuming 9% of total annual O&MC (Tsagarakis *et al.* 2003).

RIC was calculated based on *Guidelines for Performing Dynamic Cost Comparison* (DWA 2012), considering 40% of the construction cost for replacements in years 12 and 25 and 60% of the construction cost for reconstruction after 25 years.

In order to compare different scenarios, the calculated TPVs were annualized and the cost expressed as annual cash flow over the entire project period, i.e. 30 years. The annualized cost indicator also provides the possibility to compare scenarios by means of STC that represents the cost per cubic meter of treated wastewater.

Analysis of economic feasibility

Table 1 summarizes the economic analysis of the different wastewater management scenarios. Comparing the specific treatment cost (JOD/m^3) for each scenario the results indicate that the construction of a new central WWTP will be significantly more expensive than any of the three DWWM solutions. This is mainly caused by high expenses for construction of trunk lines and lift stations. Comparing different O&M options for the DWWM scenarios indicates that scenario IV, which involves a public–private partnership and benefits from selling treated wastewater, is the most favorable option. In this scenario WAJ will be in charge of the operation of the DWWM systems, while a private company will maintain them.

CONCLUSIONS

The ALLOWS GIS-based decision-support tool allows the following:

- Comparing different wastewater project options via the total project cost based on actual market values covering all investment, reinvestment and O&M cost over the life cycle of a system.
- Applying scenario analysis to compare different wastewater management solutions.
- Providing a treatment and reuse solution that is appropriate and feasible for the actual local wastewater context.
- Achieving the targeted connection degree alongside the projected population dynamics over a system's life cycle (~20 to 30 years).
- Prioritizing a decrease in the total project cost over a decrease in the initial capital investment.
- Adapting wastewater solutions to natural conditions such as topography and natural drainage in order to minimize infrastructure requirements (pumping, sewerage).
- Closing local water cycles by exploring on-site reuse opportunities (irrigation, managed aquifer recharge, landscaping, forestry) to substitute for precious fresh water resources.

The presented results show that for this case a DWWM solution is more feasible compared to a centralized approach, with cost savings of up to 40%. In the presented case O&M cost resulted as the essential criterion for economic feasibility. Significant cost savings accrue where DWWM systems are operated and maintained in clusters. This generates economies of scale in particular with respect to labor cost.

Moreover, ALLOWS provides decision-makers with an enhanced understanding of on-site conditions, with feasible solutions to improve wastewater management for any given local context as well as with all vital financial information to plan investments in wastewater infrastructure.

ACKNOWLEDGEMENTS

This paper was developed in the research project SMART – Sustainable Management of Available Water Resources with Innovative Technologies. The project is sponsored by the German Federal Ministry of Education and Research

Table 1 | Total project value summary for the scenarios I–IV in JOD (30 years, 5% discount rate)

	Scenario I	**Scenario II**	**Scenario III**	**Scenario IV**
Item	***Centralized***	***Decentralized***		
Total investment	19,840,354	10,741,188	10,741,188	10,741,188
Total reinvestment	4,604,938	2,582,440	2,582,440	2,582,440
Reuse benefits (JOD/year)	0	0	0	37,170
Total O&M (JOD/year)	245,871	364,835	243,635	206,476
TOTAL PROJECT VALUE	25,324,000	17,498,000	15,635,000	15,063,000
Annualized cost (JOD/year)	1.647.362	1.138.270	1.017.079	979.870
O&M JOD/m^3	0.66	0.98	0.66	0.56
Specific treatment cost per m^3	4.43	3.06	2.74	2.64

All cost estimates are calculated in JOD (2011, 1 JOD = 0.94 euros).

(BMBF) in the funding program 'Integrated Water Resources Management' (Project ID 02WM1080).

REFERENCES

Bieker, S., Cornel, P. & Wagner, M. 2010 Semicentralised supply and treatment systems: integrated infrastructure solutions for fast growing urban areas. *Water Sci. Technol.* **61**, 2905–2913.

Brunner, N. & Starkl, M. 2012 Financial and economic determinants of collective action: the case of wastewater management. *Environmental Impact Assessment Review* **32**, 140–150.

CEN (European Committee for Standardization) 2005 European Standard EN 12566-3 ICS 13.060.30, Small wastewater treatment systems for up to 50 PT – Part 3: Packaged and/or site assembled domestic wastewater treatment plants. CEN, Brussels.

Crites, R. W. & Tchobanoglous, G. 1998 *Small and Decentralized Wastewater Management Systems*. McGraw-Hill, New York.

DWA (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.) 2009 DWA-M-210 *Belebungsanlagen mit Aufstaubetrieb* (*Sequencing Batch Reactor*). DWA, Hennef, Germany.

DWA (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.) 2012 *Leitlinien zur Durchführung dynamischer Kostenvergleichsrechnungen (KVR-Leitlinien)* (*Guidelines for Implementing Dynamic Cost Comparison Calculations (CCM Guidelines)*). DWA, Hennef, Germany.

EC (European Commission) 2001 Extensive wastewater treatment processes adapted to small and medium sized communities. International Office of Water, Luxembourg.

Elmitwalli, T. A., Sayed, S., Groendijk, L., van Lier, J., Zeeman, G. & Lettinga, G. 2003 Decentralised treatment of concentrated sewage at low temperature in a two-step anaerobic system: two upflow-hybrid septic tanks. *Water Sci. Technol.* **48** (6), 219–226.

Engin, G. O. & Demir, I. 2006 Cost analysis of alternative methods for wastewater handling in small communities. *J. Environ. Manage.* **79** (4), 357–363.

Friedler, E. & Pisanty, E. 2006 Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. *Water Research* **40** (20), 3751–3758.

Gutterer, B., Sasse, L., Panzerbieter, T. & Reckerzügl, T. 2009 *Decentralised Wastewater Treatments Systems (DEWATS) and Sanitation in Developing Countries, A Practical Guide*. Water, Engineering and Development Centre (WEDC), Loughborough University, Loughborough, UK.

Ho, G. 2005 Technology for sustainability: the role of on site, small and community scale technology. *Water Sci. Technol.* **51**, 15–20.

Lamichhane, K. M. 2007 On-site sanitation: a viable alternative to modern wastewater treatment plants. *Water Sci. Technol.* **55** (1–2), 433–440.

Libralato, G., Volpi Ghirardini, A. & Avezzù, F. 2012 To centralise or to decentralise: an overview of the most recent trends in wastewater treatment management. *J. Environ. Manage.* **94** (1), 61–68.

Molinos-Senante, M., Garrido-Baserba, M., Reif, R., Hernández-Sancho, F. & Poch, M. 2012 Assessment of wastewater treatment plant design for small communities: Environmental and economic aspects. *Science of the Total Environment* **427–428**, 11–18.

MWI (Jordan Ministry of Water, Irrigation) 2009 *Water for Life, Jordan's Water Strategy 2009–2022*. http://www.mwi.gov.jo/sites/en-us/Documents/Jordan_Water_Strategy_English.pdf (accessed 11 April 2014).

Nivala, J., Headley, T., Wallace, S., Bernhard, K., Brix, H., van Afferden, M. & Müller, R. A. 2013 Comparative analysis of constructed wetlands: the design and construction of the ecotechnology research facility in Langenreichenbach, Germany. *Ecol. Eng.* **61** (b), 527–543.

Nogueira, R., Ferreira, I., Janknecht, P., Rodríguez, J. J., Oliveira, P. & Brito, A. G. 2007 Energy-saving wastewater treatment systems: formulation of cost functions. *Water Sci. Technol.* **56** (3), 85–92.

Orth, H. 2007 Centralised versus decentralised wastewater systems? *Water Sci. Technol.* **56** (5), 259–266.

Tchobanoglous, G., Ruppe, L., Leverenz, H. & Darby, J. 2004 Decentralized wastewater management: challenges and opportunities for the twenty-first century. *Water Sci. Technol.* **4**, 95–102.

Tsagarakis, K. P., Mara, D. D. & Angelakis, A. N. 2003 Application of cost criteria for selection of municipal wastewater treatment systems. *Water Air Soil Pollut.* **142** (1–4), 187–210.

US-BLS (US Bureau of Labor Statistics) 2012 *Consumer Price Index 2012 Consumer Price Index All Urban Consumers*. http://data.bls.gov/pdq/SurveyOutputServlet (accessed 17 August 2013).

Van Afferden, M. & Müller, R. A. 2011 Regional implementation of decentralized wastewater concepts in Jordan. *World Water Week in Stockholm*, August 21–27, Abstract Volume: 100–101.

Van Afferden, M., Cardona, J. A., Rahman, K. Z., Daoud, R., Headley, T., Kilani, Z., Subah, A. & Mueller, R. A. 2010 A step towards decentralized wastewater management in the Lower Jordan Rift Valley. *Water Sci. Technol.* **61** (12), 3117–3128.

Weber, B., Cornel, P. & Wagner, M. 2007 Semi-centralised supply and treatment systems for (fast growing) urban areas. *Water Sci. Technol.* **55**, 349–356.

Wendland, C. & Albold, A. 2010 *Sustainable and Cost-Effective Wastewater Systems for Rural and Peri-Urban Communities up to 10,000 Population Equivalents*. Guidance Paper. WECF. http://www.wecf.eu/download/2010/03/guidancepaperengl.pdf (accessed 11 April 2014).

Werz, H. & Hoetzl, H. 2007 Groundwater risk intensity mapping in semi-arid regions using optical remote sensing data as an additional tool. *Hydrogeol. J.* **15** (6), 1031–1049.

Wilderer, P. A. & Schreff, D. 2000 Decentralised and centralised wastewater management: a challenge for developers. *Water Sci. Technol.* **41**, 1–8.

First received 1 April 2015; accepted in revised form 10 July 2015. Available online 3 August 2015