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Water-Energy-Pollutant Nexus Assessment of Water Reuse Strategies in Urban Water Systems using Metabolism Based Approach

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ABSTRACT

This study analyses the water-energy-pollutant nexus performance of urban water reuse strategies by using urban water metabolism for a long-term planning period. A nexus assessment framework is developed for an Urban Water System (UWS) based on the WaterMet[2] tool to track down water, energy and eutrophication flows over the main components of the UWS. A set of key performance indicators is then selected to represent the water-energy-pollutants nexus. The suggested method is demonstrated in a real case study in Mexico for eight hypothetical reuse strategies including six greywater (GW) recycling options (decentralised) and two reclaimed water distribution (centralised) that are compared with Business As Usual (BAU) strategy ('do nothing') in the UWS. The intervention options are set up at either 10% or 50% of adoption rates (proportional to household and demands within the UWS) to be implemented at years 10 and 20. The results show that greywater strategies consume more energy than the BAU if aerated technologies are implemented but the same strategies can reduce eutrophication due to reduction of untreated discharge of pollutions into receiving water bodies and potable water saving. Combining low-energy GW options with high adoption rates results in highly efficient performance with respect to nexus approach. The proposed metabolic-nexus based approach is able to provide useful information about the performance and environmental impacts of centralised and decentralised water reuse options to support management decisions.

Keywords: decentralised water reuse, eutrophication, greywater, metabolism modelling, water-energy-pollutant nexus.

1. INTRODUCTION

There has been a lot of interest in urban water reuse as additional sources of water supply in the recent decades. Decentralised water reuse is one of management options in which wastewater is divided into greywater (GW), yellow or black water for onsite treatment and instant consumption [1]. GW (or light-greywater) is referred to the effluents of shower, hand basin and washing machine while yellow water denotes urine and black water represents toilet and kitchen effluents [2]. Using GW in buildings or households can save ~40% of the freshwater demands and simultaneously impact resource depletion and climate change [3, 4 and 5]. Information on the operation of decentralised water reuse can potentially reduce environmental impacts in cities [6, 7].

Assessments of reuse systems are more frequent in recent years using different approaches. Under the environmental view, the most widely used methodology is the Life Cycle Impact

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Assessment (LCIA) to compare impacts of Wastewater Treatment Works (WWTW) and other water management strategies [1, 7]. Another approach is the water-energy nexus analysis. Such an approach interconnects resources consumption within Urban Water System (UWS) in relation to water savings, economic costs and GHG emission using material balances, dynamic modelling, LCIA thinking, among others. The nexus has been useful to demonstrate the competitiveness of GW/RW (rainwater) against other supplies (e.g. desalinated or transboundary freshwater imports) or performance of wastewater treatments [6, 8 and 9]. In addition, some studies highlight the need to consider a pollutant nexus to give meaningful insights of operation of the water systems and health concerns [10]. Regarding the performance analysis, urban water metabolism is a comprehensive approach to simulate the key performance indicators of flows and fluxes and identify bottlenecks in the UWS. The metabolism modelling uses mass-base balances to track down water flows and other environmental flows (e.g. energy and emissions) [11, 12]. Despite the plethora of approaches, the assessment of water-energy-pollutant nexus for dynamic performance of water reuse schemes in UWS have not been addressed much in detail. Thus, a comprehensive and detailed framework of such an analysis are needed to explore water reuse strategies.

This study aims to analyse the performance of a set of hypothetical GW strategies based on a nexus-metabolism approach, using a real-world case study. The rest of the paper presents the methodology and case study followed by results and discussion, and concluding remarks.

2. METHODOLOGY

The framework used in the study compares the performance of centralised and decentralised reuse strategies throughout a combined nexus-metabolism approach. WaterMet^2 modelling tool was used here to simulate the performance of urban water metabolism in UWS [13]. WaterMet^2 is a conceptual mass-balance based model which is able to quantify flows of water and other environmental fluxes such as direct and indirect energy and eutrophication emissions within the boundaries of the UWS for a long-term planning horizon. The model uses a Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA). A set of key performance indicators was derived from urban water metabolism simulation in WaterMet^2 to form the analytical framework of water-energy-pollutants nexus for a number of water reuse strategies.

2.1 System boundaries

The UWS boundaries include three main subsystems of water supply, subcatchment and wastewater. The water sources and sinks are the water boundaries i.e. groundwater extraction and receiving water bodies for discharging treated/untreated wastewater. They also include processes directly affecting the operation such as chemical manufacture and allocation in the field, power use and generation, sludge management and fertiliser avoidance. The construction and disposal stages were excluded from the analysis as well as energy consumptions in households through appliances and fittings. The results were referred to the 1m^3 of water supplied, reclaimed and reused in accordance with previous studies [1, 14].

2.2 Performance indicators

Three performance indicators were proposed to analyse the metabolism performance and the nexus. All the analysis is based on daily water simulations of demands and distribution within the principal sub-systems of the UWS, according to the method stated for WaterMet^2 for a long-term period (here 30 year planning horizon) [14]. The indicators were calculated as follows:

2.1.1 Water saving

The water saving represents the reduction of water withdrawals relative to the BAU state. The percentage of water saving were calculated as:

$$Sw = \frac{Ws_{BAU} - Ws_{si}}{Ws_{BAU}} x100 \quad (1)$$

where S_w is the saved water (%); W_{SBAU} is the total water supplied by BAU (m^3/y); W_{SSi} is the total water supplied by strategy *i* (m^3/y).

2.1.2 Energy consumption

The net energy consumption considers direct energy sources from grid electricity and indirect energy embodied in chemicals (e.g. sodium hypochlorite and ferric chloride) and fuels (e.g. diesel). It also takes into accounts renewable energy produced in the wastewater treatment works such as biogas-electricity conversion:

$$TE = EE + EF + ECh + Ed - EBp - Eernw \quad (2)$$

where *TE* is the total net energy use; *EE* is the electricity provided by the network; *EF* is the energy obtained from burning fossil fuels (e.g. diesel); *ECh* is the energy embodied in the chemical products used in water or wastewater treatment (e.g. chlorine); *Ed* is the electricity used in distribution; *EBp* is the embodied energy in by-products which substitute fossil fuels or fertilisers, and *EErnw* is the electricity obtained from renewable sources. All values in kWh/m^3.

Energy inputs of different water technologies were taken from data reported in the literature and Ecoinvent database [15] as specified in Tables 1 and 2. The energy used in water distribution networks was calculated using 70% efficiency in pumps.

2.1.3 Eutrophication

Eutrophication is the impact category representing the pollution of Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphorus (TP) in PO_4eq/m^3. A net balance was obtained similarly to the energy, accounting for direct and indirect flows. The net balance considered the avoided fertilizer production of urea (40%) and single superphosphate. Results are in gPO_{4eq}/m^3.

2.2 Strategies

The strategies comprised eight hypothetical intervention options including six decentralised and two centralised water reuse methods. The decentralised greywater options included Rotational Biological Contactor (RBC), Membrane Biological Reactor (MBR) or Vertical Constructed Wetlands (VCW) treatments. All treatment technologies reported removal efficiencies above 90% of Biochemical Oxygen Demand (BOD) for greywater treatment. Two centralised options were based on the existing Activated Sludge treatment. The strategies were set up to be implemented at two stages at years 10 and 20, within two rates of adoption 10% and 50% based on the preferences obtained from key experts (data not shown). Table 1 presents a summary of the main assumptions for operating such technologies. The strategies considered an increment of population rate from 1-3% along the planning horizon. All decentralised strategies assume that they collect greywater (i.e. from the hand basin, shower and washing machine) and recycle the treated greywater for the provision of toilet flushing and irrigation uses.

Table 1. Strategies analysed in the study

Secondary process	Strategy acronyms	Implementation rates (%)		Energy in WW treatment (KWh/m³) [16]–[18]	Efficiency (%)[19]–[21]
		2025	2035		
Decentralised (D)					
Rotational Biological contactor	RBC10%	5	5	1.6700	COD 88%; TNK 71%; TP 58%; BOD 95%; TSS 86%
	RBC50%	20	30	0.7224	
Membrane Bioreactor	MBR10%	5	5	2.2200	COD 64%; TN 79%; TP 91%; BOD 95%; TSS 98%
	MBR50%	20	30	0.9000	
Vertical Constructed Wetland	VCW10%	5	5	0.1724	COD 81%; TN 69%; TP 71%; BOD 100%; TSS 98%;
	VCW50%	20	30	0.3724	
Centralised (C)					
Conventional Activated Sludge	C10%	5	10	0.25	COD 90%; TN 60%; TP 60%; BOD 94%; TSS 91%;
	C50%	20	30	0.36	

2.3 Case Study

The modelling framework was tested in a real-wold case study in the region of San Francisco del Rincon (SFR) and Purisima del Rincon (SFR) cities, Guanajuato, Mexico. The UWS consists of two independent water potable systems and one wastewater treatment and reuse sub-system. Figure 1 presents a simplified layout of the configuration of the UWS. Groundwater from Turbio Aquifer is the only source of potable water in this region. Potable water is obtained through extraction of 23 boreholes, each one with chlorine dose of Cl_2 or NaOCl. The potable water is stored in elevated tanks and distributed by gravity through the drinking water network to the 114,651 urban dwellers [22]. Domestic supply varies from 90 up to 180 l/cap/d [23], less than the 250 l/cap/d recommended for similar areas in Mexico [24]. This situation is due to the potable water leakages (40-50%) and the semiarid climate. To cope with such water constraint, there is a water reuse scheme made up of "San Jeronimo" WWTW plus a non-networked reclaimed water distribution. The WWTW has a capacity of 21,600 m^3/d, the inflow belongs to 60% from SFR and 40% from PR. The reactor uses an activated sludge treatment, coupled with primary and secondary sedimentation and UV or chlorination disinfection stages. The plant was designed to treat the effluent at a quality of 30 mg/L BOD to comply with the non-potable water reuse guideline in Mexico [25]. The users of reclaimed water are mainly the local water utilities and the construction industry, which transport the water using 20 m^3 tank lorries per journey to the parks or construction sites. Reuse rates reached only one percent of the treated wastewater in 2015 [26]. This estimation might increase due to the current construction of a distribution network of reclaimed water of a 250 m^3/d. In addition to the water reuse, the sewage sludge sources two by-products: electricity and fertilisers. An anaerobic digester stabilises the sludge and produces biogas at rates of 47.5 m^3/h. A pressure container stores the biogas and sends 45% of the total volume to the electricity generator. The system produces 0.03 kWh/m^3 which supplies 40% of the electric self-operation demand [26]. Unused biogas is burned before being released into the atmosphere. Dewatered stabilised sludge is often deposited into agricultural fields nearby.

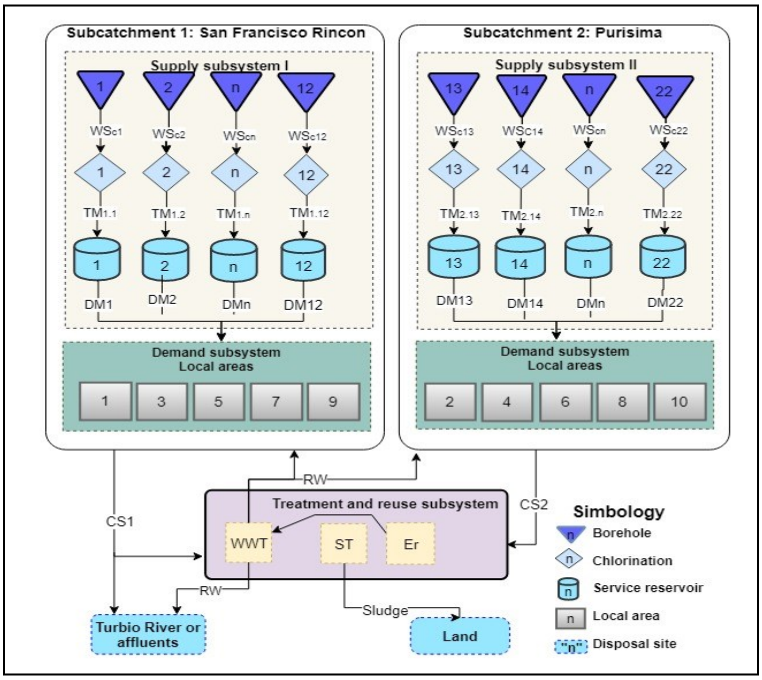

Figure 1. Main components of the UWS in the case study

WSc: Water supply conduit; TM: Trunk main; DM: Distribution Main; CS: Combined sewer; WWT: Wastewater Treatment; ST: Sludge Treatment; Er: Energy recovery; RW: Reclaimed water

2.4 Inventory data

All input data and main assumptions referred to the context of the region in study in Mexico. As such, the primary data was acquired from different Mexican institutions and water utilities. The missing or secondary data were obtained from relevant literature and Ecoinvent database as stated in Table 2. Data were not normalised due to uncertainties specified in the context of the case study.

Table 2. Main data inputs of the case study

Category	Input data
Climatic data [27]	Daily recorded data of rainfall, evaporation, and temperature from 1962-2012 in *Guanajal* station
Area [22]	Total area 2844 ha: 58% pervious area, 26% impervious area, 16% roads
Demographic data[22]	Total population 1990-2010, Total households: 24,751. Occupancy per household: 4.4,
Potable water sub-systems[26]	Daily water extraction, energy consumption and chemical use (2015-2016) in San Francisco and Purisima, Mexico.
Wastewater inflow and effluent[26]	Daily flows and wastewater quality, Remotion rates (COD 90%, TN 60%, TP 60%) Electricity 0.38 kWh/m^3
Sludge	Quality, biogas production, and disposal rate
Impact factors database [15]	Cumulative Energy demand Eutrophication CML 2001, world values

3. RESULTS AND DISCUSSION

The eight intervention strategies outlined above were analysed in the case study by using urban water metabolism for a period of 30 years. The metabolism performance of the strategies is then compared by using water-energy-pollutant nexus framework to identify the more appropriate strategies in this context.

3.2 Water performance

The water saving of implementing centralised and decentralised strategies within the UWS is shown in Figure 2. The water saving depends on the adoption rate regardless of the technology in use. Hence, the results were grouped as centralised and decentralised for 10% or 50% adoption rate (D10%, D50%, C10% and C50%). Demand for larger proportions of reclaimed water decreases 1.7% and 7.8% of groundwater withdrawals at 10% and 50% adoptions rate, respectively. Subsequently, decentralised reuse reduced the inflows into the sewerage and wastewater treatment, while centralised had no effect. This is because centralised schemes gather the reclaimed water at the end of the WWTW, reducing the effluent into the river. The saving obtained in the study were smaller than those reported by Duong et al., (2011) [3], and Opher and Friedler (2016) [1] for similar water reuses. The possible differences are in modelling the gradual adoption rates and the low demand for toilet and irrigation for such adoption rates in the case study.

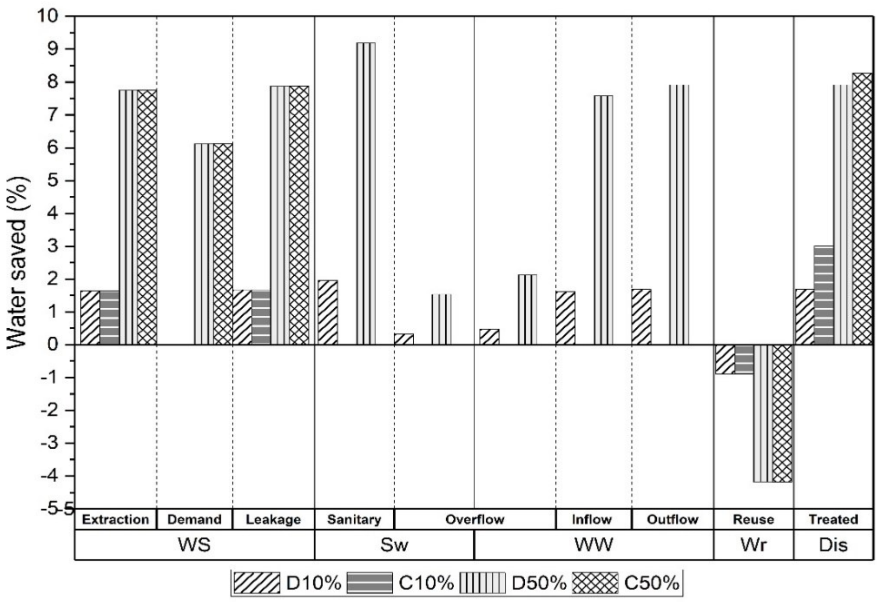

Fig. 2. The proportion of water saved per subsystem component
D: Decentralised; C: Centralised; WS: Water Supply, Sw: Sewerage; WW: Wastewater treatment; Wr: Water reuse and Dis: Discharged.

3.3 Energy

Energy consumption, both direct and indirect, was analysed in the long-term for each of the strategies proposed (Figure 3a). Results indicate that technology used and adoption rates affect the energy use. Decentralised greywater schemes outperform the BAU with respect to energy consumption only when MBR or RBC technologies are used. This is because such technologies consumed additional electricity for the aeration modules, while wetlands and centralised reuse use an extra pumping system. Among the strategies analysed, the VCW50% and C50% have lower energy consumption, due to the reduction in groundwater withdrawals, and even further, the VCW50% due to its low energy requirements.

3.4 Eutrophication

Eutrophication impact category represents the pollution of N, P and COD into the urban area. The eutrophication produced by BAU and each strategy is variable over the planning horizon, as can be seen in Fig. 3b. The highest reduction was estimated by 2044 for the MBR50% and VCW50% from 44 gPO_{4eq}/m^3y in BAU to 41.8 gPO_{4eq}/m^3y in MBR. Fewer adoption rates (e.g. VCW10%) do not reduce significantly eutrophication emissions.

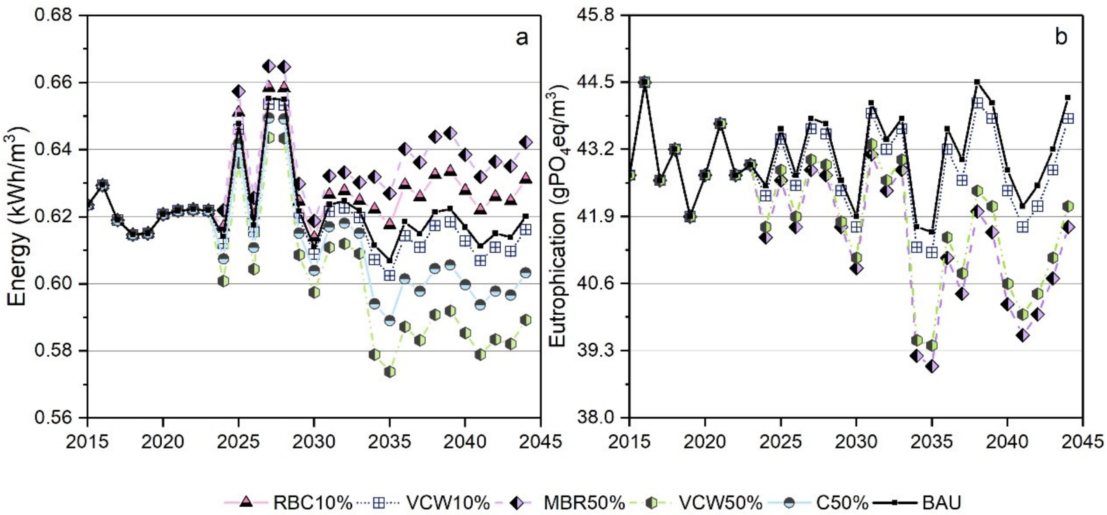

Fig. 3. Energy consumption (a) and Eutrophication potential (b) over the planning horizon for core selected strategies

4. CONCLUSION

This study presents a nexus-metabolism framework to analyse the performance of the UWS when water reuse strategies are planning for implementation in a real-world case study in Mexico. The model used material flow balances, LCA, and indicators to evaluate energy-water and eutrophication-water of selected water reuse strategies, considering pre and post-consumption stages. From the results, it can be concluded that reusing water reduces the water withdrawals and eutrophication generated, but the energy consumption depends on both, centralisation level and adoption rates. Combining low-energy GW systems with high adoption rates would result in highly efficient from the perspective of water-energy-pollutants nexus. The framework showed its usefulness to provide information on the performance and facilitate decisions among water managers. Analysis of combining these three approaches can provide a better understanding of the nexus influence of the strategies in UWS which can be further investigated in future work.

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COMPETING INTERESTS

The authors certify that they have no affiliations or involvement with people or organisations that might have an interest in the submitted manuscript.

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