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The challenge of dry-weather sewage intakes as a sustainable strategy to develop urban sanitation in the tropics

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Abstract

Informal housing, and operational and management deficiencies, influence sewerage system performance in Brazil. Inadequate sewage volumes in storm sewers lead to fecal contamination and affect recreational water environments. As overflow structures, dry-weather sewage intakes (DWSIs) are used to intercept and transfer sewage from storm- to sewage- sewers. For cities without public services, the DWSI strategy has been suggested as an option to enable easier and more rapid responses in terms of sewage pollution control. The strategy may also lead to gradual construction of a separate sewerage system in a two-step plan: initially, based on the construction of DWSIs and wastewater treatment plants, and then, on the construction of separate sewers. The paper is a discussion of the main technical challenges in sustainability of the DWSI strategy, and includes a case study of slum and other informal housing areas in Rio de Janeiro.

Key words: separate sewerage systems, sewage pollution, storm sewers, tropical climate, wastewater

INTRODUCTION

In general, Brazilian cities have tropical or sub-tropical climates, and the typical rainfall regime comprises infrequent, high intensity events. During the summer, 30-day rainfall accumulation can be up to twice that observed in dry weather periods. In the wet season, a 1-hour event in Rio de Janeiro can yield up to 120 mm of rainfall (10-year return period), the same as the full, historic, average 30-day, accumulated rainfall (GEORIO 2019).

In order to deal with very high and extreme rainfall and peak discharges in tropical climates, a combined sewerage system would need to offer substantial hydraulic capacity. Due to the low frequency of rainfall events, occurring mostly in summer, however, such hydraulic capacity is likely to be underused and operate under dry-weather flow most of the time. The typical storm flow from 1.0 ha of urban catchment arising from tropical rainfall can be equivalent to the total sewage flow of 55,000 inhabitants (Tsutiya & Bueno 2005). Evaluating a hypothetical urban catchment under typical tropical rainfall, and allowing for different topographic gradients and population densities, Mutti (2015) reported the generation of storm flows equivalent to between 63 and 573 times the sewage flow.

Cities in temperate climates are different. Combined sewerage systems there deal with frequent, low intensity rainfall. Brazilian cities, with their typical rainfall regimes, use separate sewerage systems. This is the main reason why separate sewerage systems have been recommended in Brazilian sanitary engineering since the end of the 19th century. The Brazilian option for separate sewerage systems is not a dogmatic precept but a technical issue.

Both combined and separate sewerage systems are complex to operate and difficult to maintain to achieve high performance levels (Balkema *et al.* 2002; Cardoso *et al.* 2004; van Riel *et al.* 2014). Operational and management deficiencies influence the performance of separate sewerage systems, and

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the inadequate sewage volumes in storm sewers during dry or wet periods leads to fecal contamination, and affects recreational water environments and other beneficial water uses (Sercu *et al.* 2009, 2011).

The main sources of fecal contamination of storm flows in Brazilian sewerage systems are: (1) illegal dwelling connections; (2) temporary connection between sewage and storm sewers for emergency maintenance; (3) pumping station overflows due to mechanical or electrical failure; and (4) continuous increases in sewage flow from slums and informal housing in areas where separate sewerage system implementation, operation, and maintenance becomes very difficult (Volschan & Silva 2007; Volschan & Jordão 2013; Volschan *et al.* 2017).

Dry-weather sewage intakes (DWSIs) are used to improve the performance of separate sewerage systems where storm sewers must deal with sewage. The design of the DWSI is similar to a combined sewer overflow structure. During dry weather flow, sewage is intercepted by the DWSI and transferred from storm to sewage sewers. In order to protect recreational water environments, the strategy is applied mainly to improve the performance of separate sewerage systems in large coastal Brazilian cities, such as Rio de Janeiro and Salvador, for a long time, and Florianópolis more recently.

Brazil still faces the challenge of urban sanitation. The last national official survey (SNIS 2019) indicates that around 60% of the population received an urban sewage service and just 40% a wastewater treatment service.

Many Brazilian cities now propose the gradual construction of separate sewerage systems, following two-step plans comprising; initially, the construction of DWSIs and wastewater treatment plants, and then, later, of separate sewers. The concept is widespread in the Brazilian water sector as an innovative model for planning sewerage infrastructure investment, enabling more rapid response in terms of urban pollution control than conventional systems.

The basis of the concept is that DWSIs will have the prime function of intercepting and transferring dry-weather flows to wastewater treatment plants and, later, after the construction of separate sewers, assume their original function of protecting watercourses by inhibiting the entry of sewage into storm sewers.

Investment planning using this model should offer a more robust sewerage infrastructure at the end of the plan, not just through the conventional separate system, but also due to the DWSIs then being able to control pollution from storm sewers and increase the efficiency of the whole system.

The gradual construction of separate sewerage systems using the two-step plan and DWSI strategy was applied in the northeast coastal region of Rio de Janeiro state to control sewage discharges from the cities of Araruama (population equivalent of 130,000 inhabitants), Iguaba Grande (28,000 inhabitants), São Pedro de Aldeia (103,000 inhabitants) and Cabo Frio (223,000 inhabitants), and to improve the water quality in Araruama lagoon. Petropolis (306,000 inhabitants) and Nova Friburgo (190,000 inhabitants), in the mountain region of the state, followed the same strategy some years ago, and Teresopolis (181,000 inhabitants) and Marica (156,000 inhabitants) are now discussing using it. Even though technical discussion is limited, the Rio de Janeiro Metropolitan Development Plan argues that application of the DWSI strategy represents the ideal means for gradual implementation of separate sewerage systems in the municipalities around Guanabara Bay (Câmara Metropolitana 2018). The Brazilian National Congress is now discussing review of the Water Sector Federal Law, and the DWSI strategy is set out as an acceptable solution for the initial and temporary provision of separate sewerage in Brazilian municipalities.

Even though good results may be achieved through this model, care, understanding and technical agreement are needed between stakeholders to gain the most from the concept and avoid its negative points. Brazilian cities face economic and political opportunities for the planning and expansion of sewerage systems, and the DWSI strategy option still requires official technical guidelines.

This paper is intended to set out the basic concepts relating to urban wastewater engineering and to discuss technical challenges to the sustainability of the DWSI strategy. Concepts and technical issues

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are highlighted through practical results obtained from a DWSI strategy plan developed for the interception of sewage from 140 slums, to minimize water pollution of the Jacarepagua and Barra da Tijuca watershed in Rio de Janeiro.

DISCUSSION

Basic concepts

Urban infrastructure is necessary for any city to offer social, economic and environmental quality to society. Without it, poor health, poverty, and pollution prevail. Urban water environments depend on sewage pollution control, which can only be achieved through an adequate sewerage infrastructure. Cities that do not have an adequate sewerage system do not present high urban development or human indices (Gandy 2004; Loucks & van Beek 2017).

A logical understanding of the problem indicates that infrastructure is the main object and that pollution control is the means of achieving the goal in terms of urban water quality. Considering the view from water to land, rather than the reverse, represents a change in the water pollution control paradigm. Instead of control based just on water quality indicators, it must also relate to infrastructure management indicators. In this context, the hydrologic and hydraulic issues related to the tropical climate mean that separated sewerage systems will always be the main objective, and the use of the DWSI strategy cannot be deemed an adequate final proposal, just an intermediate and temporary one.

On the other hand, it must be remembered that sewage collection and transport through storm sewers during the first and temporary step, as proposed by the DWSI strategy plan, do not represent the configuration of a formal combined sewerage system, but just the use of separate storm sewers. Combined sewerage systems are planned and designed according to specific criteria and parameters that differ from those for separate storm sewers (May *et al.* 1996; Nalluri & Ghani 1996). In Brazil, sewage sewers are designed on the basis of self-cleansing criteria and storm sewers according to minimum velocity criteria (ABNT 1986).

Technical aspects

Pavement surface drainage

Watershed topography and street slope may allow the use of pavement surface drainage instead of storm sewers. For around half of Brazilian streets, the DWSI strategy cannot be applied because in these cases separate storm water sewers are not required (Tsutiya & Bueno 2005).

DWSI strategy efficiency

Determination of the efficiency of the DWSI strategy in terms of pollution control must be based on the magnitude and frequency of overflows and the load of pollutants, which depends on the use of robust hydrologic and hydraulic models (Lau *et al.* 2002; Mailhot *et al.* 2015).

The location of DWSIs close to the pollution sources protects the entire watershed environment. If located close to the mouths of small rivers, channels, and creeks, they are able to protect only those watercourses downstream of them.

DWSI strategy efficiency depends on rainfall intensity, duration, and frequency, on watershed size and slope, and on the runoff coefficient and population density. Frequent high intensity, long duration rainfall events, and higher power dynamics in terms of flow propagation through the watershed, make the DWSI strategy less effective (Zawilski & Brzezińska 2014).

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Overflow and impacts on water quality downstream

Overflow and pollutant load measurements based on suspended solids, organic matter and nutrients must be analyzed to evaluate water quality effects on downstream watercourses. Evaluation requires hydrologic and hydraulic modeling of the complete urban water system based on water quality tools (Soonthornnonda & Christensen 2008).

The DWSI strategy can be improved to minimize the effects of pollutant loads using on-site treatment based on wetlands, and mechanical and physico-chemical processes (Montalto *et al.* 2007). Recreational water environments must be protected from pathogenic contamination and disinfection could be required (Chhetri *et al.* 2016).

Use of combined sewer overflows is heavily restricted under international environmental guidelines. The frequency and magnitude of overflow events are restricted, and retention-detention devices and on-site treatment can be required (de Toffol 2006).

Impacts on separate sewerage systems

Sewerage systems can be affected by hydraulic overload in wet weather, by the presence of coarse solids and grit, and by saline intrusion.

Hydraulic overload. The DWSI strategy depends on the hydraulic capacity of the existing separate sewerage system to accept both the mixed sewage and phreatic recharge flow in dry weather, and sewage, phreatic recharge, and stormflow in wet weather. Separate systems can overflow when their capacity is exceeded in wet weather, as a result of infiltration and stormwater inflow (Rutsch *et al.* 2008).

Hydraulic connection between a DWSI and a separate sewerage system can be achieved by gravity or pressure flow, but the intake must be designed to operate by influent gravity flow (sewage and phreatic recharge) in dry weather, to avoid jet-flow close to the screens. In wet weather, however, depending on rainfall magnitude and the hydraulic profile upstream, the intake will accept a higher inflow and may work under pressure.

During the first flush, large quantities of pollutants can be discharged to receiving waters and stormwater runoff has been identified as a leading cause of degradation in receiving water quality (Saget *et al.* 1996; Deletic 1998; Lee *et al.* 2002; Barco *et al.* 2008). DWSIs can be designed to attend a higher inlet flow to admit the first flush from the urban pavement. This hypothesis contributes to the control of runoff pollution and increases DWSI strategy efficiency.

DWSI strategy, as applied on small rivers, channels and creeks, must be designed to maintain minimum ecological flows on water courses downstream and to guarantee the hydrologic balance of the watershed as a whole (Bunn & Arthington 2002; Rolls & Bond 2017).

The hydraulic capacity assessment of separate sewage systems broadens the modeling of the entire urban water system. The hydrologic, hydraulic and water quality tools used must also take into account the technical constraints imposed by the behavior of the existing sewage system (Murla *et al.* 2016).

Optimization of the DWSI strategy depends on modeling of the complete urban water system. Higher influent flows increase pollution control efficiency, but also have higher impacts on the operation, maintenance, and reliability of the existing system. DWSI hydraulic capacity must be defined, therefore, in relation to the influent and effluent flow data, and the pollutant concentration and loads.

Coarse solids. Many developing countries do not have the infrastructure to manage urban solid waste. Litter tends to find its way into storm sewers, ending up in streams, rivers, and the sea (Armitage & Rooseboom 1999; Marais & Armitage 2004).

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To prevent pipes and pumps clogging, and general damage to the sewerage system, DWSI designs must include screens to remove the rags and debris, and both coarse and floating solids, carried in storm sewers, small rivers, channels, and creeks, especially in wet periods.

Grit. Mineral particles are often carried through storm sewers or along watercourses. DWSI design must include a grit removal chamber to avoid mineral particle deposition in downstream sewers, abrasion of pumps and pipes, and excessive loads of settleable solids entering wastewater treatment plants (Ashley *et al.* 2000).

Separate sewers are designed in Brazil on the basis of self-cleansing criteria and a tractive stress of 1.0 Pa is required to avoid sewage solids sedimentation in sewers. Depending on grit particle size, however, self-cleansing sewers can require higher tractive stress of up to 9.0 Pa (Gupta 2008).

Grit sedimentation in pumping station sumps can be increased due to interruptions in pumping; for example, arising from equipment failure. Deposits may appear inside equipment, and inlet and discharge pipes, leading to hydraulic head losses and clogging. The geometric design of the sump must be optimized to avoid solids deposition (Li *et al.* 2019).

Mineral solids suspended in sewage are also potentially abrasive due to the presence of silica, and friction forces lead to a gradual loss of material from pump impeller vanes and suction inlets. To minimize pump efficiency decreases, equipment can be protected against abrasion by applying ceramic coatings or using steel with high chromium content.

Installing a grit chamber close to a DWSI also reduces the grit load on the conventional grit chamber at the wastewater treatment plant head.

Saline intrusion. Salinity affects wastewater biological treatment plants and DWSIs must be protected from the saline intrusion that can occur at high tide (Kincannon & Gaudy 1968; Wang *et al.* 2005). Figure 1 shows a low dam designed to protect a DWSI from saline intrusion.

Fluctuations in wastewater characteristics. Wastewater quality may fluctuate strongly in relation to rainfall intensity and duration, and DWSI design may impact unit operating performance at wastewater treatment plants (Leitão *et al.* 2006). Equalization tankage, as used with combined sewerage systems, may be necessary at the head of the conventional flow diagram to minimize effects of fluctuations in wastewater characteristics on treatment process performance.

Impacts on storm drainage sewers

The temporary use of storm drainage sewers under the DWSI strategy may impact urban infrastructure by increasing flood risk, as well as creating opportunities for malodorous emissions and for concrete pipe corrosion (Ashley *et al.* 2000).

Flood risk. DWSIs are constructed inside storm sewer manholes or on small rivers, channels or creeks, according to different models: (i) low dam and weir and (ii) low trench and weir (Figure 1). The first type is easier to construct and install, but requires elevation of the hydraulic profile upstream and configuration of a singular hydraulic head loss. The latter may affect storm drainage system operation and increase the urban flood risk.

Malodorous emissions. The tractive stress required to prevent the deposition and accumulation of organic particles cannot be guaranteed in storm sewers. Anaerobic decomposition of organic matter can lead to the generation of bad odors including the emission of hydrogen sulfide (Park *et al.* 2014).

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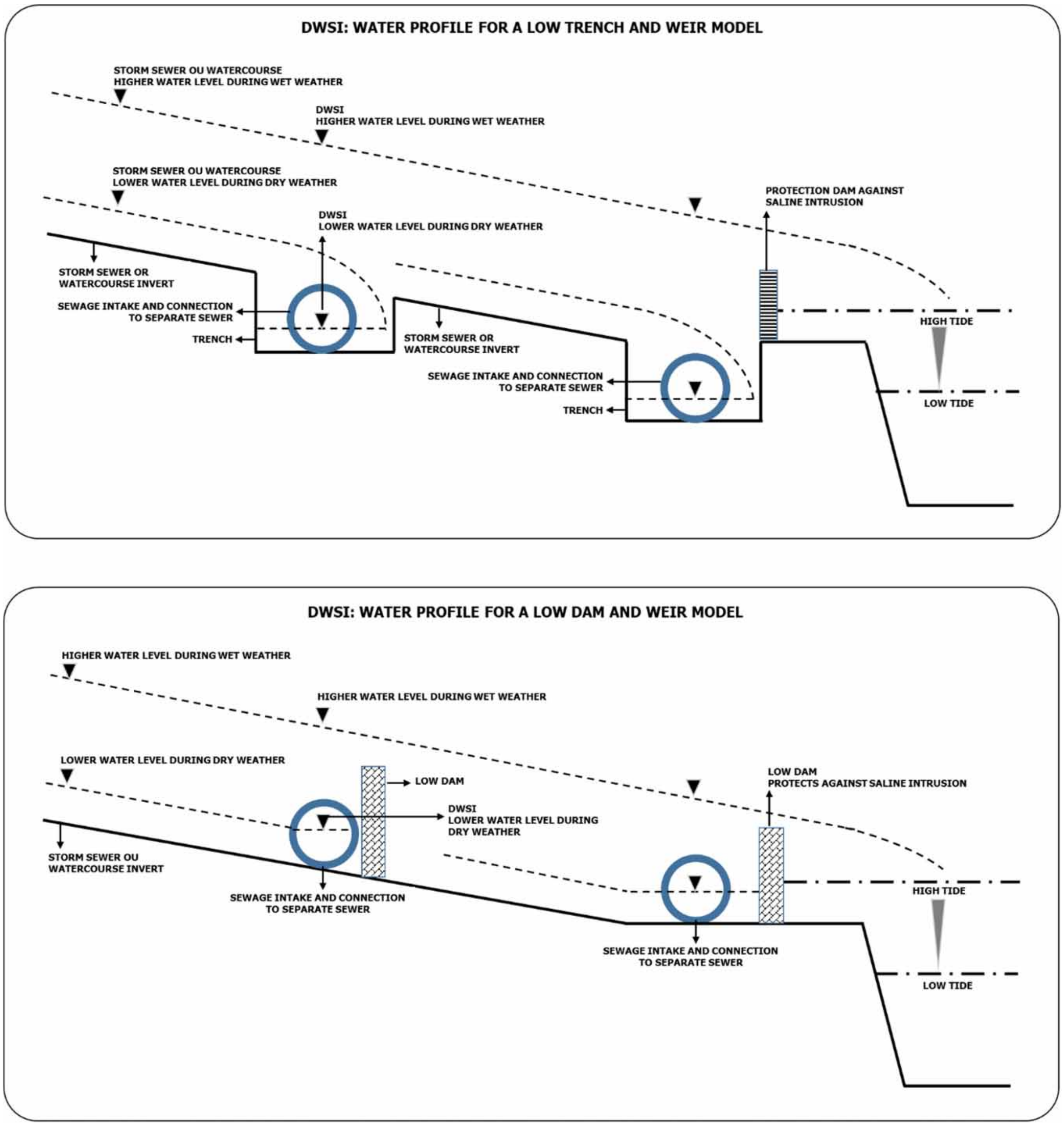

Figure 1 | DWSI design models: low dam and weir below, and low trench and weir above.

Concrete pipe corrosion. Solids accumulation leads to the oxidation of hydrogen sulfide to sulfuric acid, creating the atmosphere required for concrete corrosion; for example, of storm sewers, and the resulting reduction in the life cycle of urban infrastructure (Jiang *et al.* 2016).

Adequate DWSI strategy plan, design, and construction

The gradual implementation of the separate sewerage system through DWSI strategy requires changes to main sewer design and construction between DWSIs.

Main sewer construction between DWSIs along – that is, within – watercourses does not form part of a conventional sewerage system master plan and could lead to hydraulic losses and increases in the watercourse hydraulic profile. Pipes installed along watercourses also interfere with the general view of the urban water environment (Figure 2).

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Figure 2 | A main sewer constructed between DWSIs along a watercourse.

DWSI strategy must be planned, and DWSIs designed and constructed following standard guidelines and best engineering practice, at the same technical level generally involved in implementing urban water infrastructure. DWSI strategy cannot be part of an urgent solution intended to control sewage pollution.

Economic assessment of DWSI strategy

Like any conventional urban water project, the feasibility of DWSI strategy depends on economic assessment in terms of CAPEX, OPEX, service revenue and cost-benefit. DWSI efficiency in controlling sewage pollution can also be quantified on the basis of an economic view.

During the period of operation under DWSI strategy and storm sewer use to collect sewage, which is typically quite short, the tariff structure for sewerage service provision must be reorganized to take account of the real expenditure for constructing, operating and maintaining the temporary system.

Institutional framework for the DWSI strategy

Inadequate housing and slums are important sources of sewage pollution, and contribute to the inefficiency of separate sewerage systems. Under the Brazilian legal framework, municipalities are responsible for licensing housing. Housing and sewage pollution control are very closely connected, and urban watercourse quality will only be good if the challenge of unregulated housing is overcome.

Storm drainage systems are operated by municipal agencies independently of sewerage systems, however, the latter commonly being the province of water companies. DWSI strategy relies on the operation and maintenance of DWSIs, and requires an institutional framework and adapted regulation mechanisms to improve dialogue between urban public agencies.

Barra da Tijuca and Jacarepaguá watershed: 195 slums in Rio de Janeiro

Although structural, operating and maintenance failures all compromise the efficiency of the local separate sewerage system, the environment of the Barra da Tijuca and Jacarepaguá watershed in Rio de Janeiro is impacted most severely by the city's disorderly urban expansion. The combined catchment, which covers 280 km², is drained to a coastal lagoon system by 12 tributaries, with a single outlet to the sea (Figure 3). Around 900,000 people live in the urbanized parts of the watershed, one-third of them in informal housing or squatter areas in a group of 195 slums (IPP 2019).

To minimize watercourse pollution from uncontrolled sewage discharge, the State Water and Sewerage Company has proposed a master plan based on the DWSI strategy and two main guidelines. The first is the prioritization of DWSI installation in line with the storm sewer rather than the open

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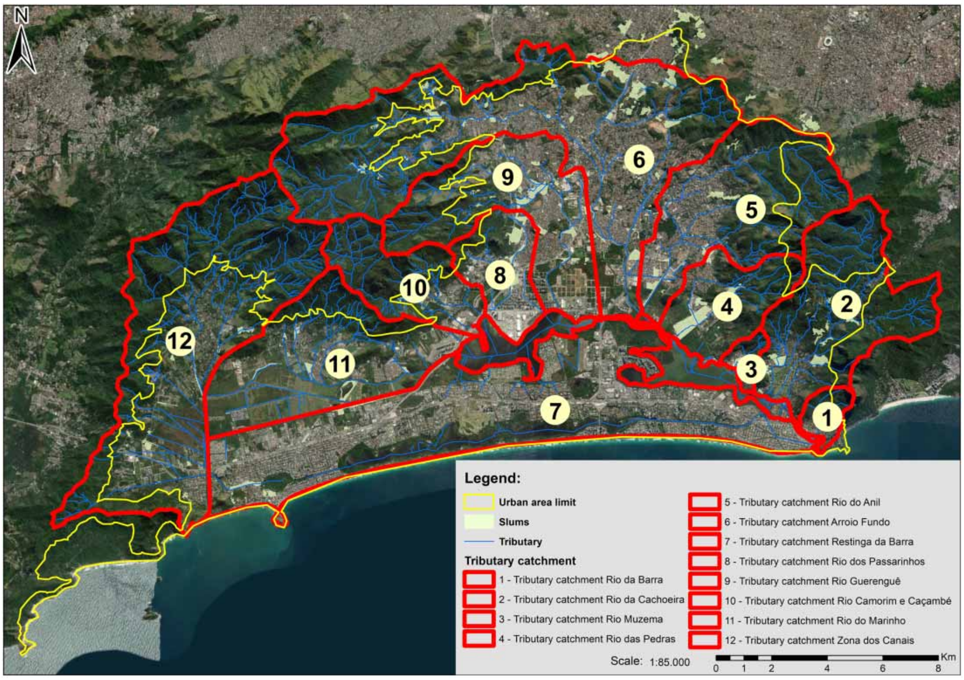

Figure 3 | Barra da Tijuca and Jacarepaguá watershed, Rio de Janeiro, Brazil.

watercourse model. The second, prioritization of DWSI location upstream of and close to pollution sources, to protect the entire combined watershed environment (COPPETEC 2018).

The plan includes the conceptual design of 132 DWSIs, 86 based on the storm sewer model and 46 on the open watercourse model. The entire plan was modeled hydraulically using commercial software to investigate potential hydraulic overload of the existing sewerage system. The overflow through each DWSI was quantified in terms of the number of events, and magnitudes of the BOD and P loads.

The modeling results indicated that the DWSI strategy would enable the interception, on average, of 11 tonnes of BOD per day – an efficiency of 86% in terms of sewage pollution control. More than 50% of the DWSIs could achieve efficiencies exceeding 90% and only 10% would yield efficiencies lower than 35%. As noted, lower efficiencies arose when rainfall event intensity, duration, and frequency were higher, as when the catchment area slope, runoff coefficient, and/or population density were higher.

The average total solution CAPEX, taking the DWSIs, screens, grit chambers, and gravity or pressure connections to the sewerage system, including pumping stations, was US$209,000 per DWSI on the storm sewer model and US$456,000 on the watercourse model. The 'DWSI' value represents an investment equivalent to US$150 per inhabitant.

CONCLUSION

The application of DWSIs as part of a two-step implementation plan for new separate sewerage systems may be an easier way to achieve urban pollution control more rapidly than the conventional one. In both cases, however, care and attention to important technical issues are required, to gain the benefits of the proposal and avoid its negative points.

A DWSI strategy must be based on formal technical guidelines and several issues have been raised in this paper that must be considered in construction and implementation.

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The results obtained in the Barra da Tijuca and Jacarepaguá combined watershed show that the DWSI strategy can achieve good sewage pollution control and improve the efficiency of existing separate sewerage systems.

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