

Assessing the risk to downstream water quality posed by domestic wastewater and developing spatially optimized investment programs to reduce this risk.

Stewart, M.¹, Smolders A.¹, Thompson C.¹ and Marsh, N.²

1. Seqwater, 117 Brisbane Street, Ipswich, QLD, 4305. Email: morag.stewart@seqwater.com.au

2. Truii Pty Ltd, 8/88 Boundary Street, West End, QLD, 4305

Key Points

- Pathogenic microorganisms found in wastewater present a potential hazard to public health and the safety of drinking water; other contaminants found in wastewater present a hazard to aquatic ecosystems.
- There are over 42,000 domestic On-site Sewerage Facilities (OSFs) across SEQ drinking water source catchments which treat wastewater in areas not serviced by centralized sewage systems.
- A desktop-based analysis was developed to estimate the total daily loads of potentially pathogenic microorganisms arising from OSFs and the level of risk to adjacent streams and downstream freshwater environments.
- Application of an optimization model allowed an in-catchment intervention program targeting high risk OSF to be developed, with modelling suggesting a considerable reduction in pollutant loads can be achieved with targeted investment.

Abstract

Domestic wastewater contains high levels of potentially pathogenic microorganisms. In residential areas not serviced by reticulated municipal sewage networks, domestic wastewater is treated via On-site Sewerage Facilities (OSFs). However, the failure rate of OSFs is reportedly as high as 70%, which can result in contamination of waterways and adversely impact on water quality. We developed and applied a spatial analysis method in combination with the Catchment Investment Decision Support System to (1) estimate total daily loads of potentially pathogenic microorganisms arising from OSFs and the level of risk to water quality, and (2) to develop an optimised catchment intervention program to reduce loads of potentially pathogenic microorganisms entering waterways in southeast Queensland. There are over 42,000 OSFs present across catchments in SEQ. Here we present results from Canungra Creek catchment with 215 OSFs, 55 assessed as posing at high-or very high risk to water quality. Daily loads of bacteria and viruses can be reduced from 7.1 log to 6.0 log, and daily loads of protozoa can be reduced from 3.1 log to 2.0 log via upgrade of 52 problematic OSF. The outputs also provide mapping of areas which have the most impact on stream water quality.

Keywords

On-site sewerage facilities; pathogens; spatial analysis; drinking water source catchments; catchment investment; decision support system

Introduction

Water resource managers and utilities responsible for drinking water have a duty of care to provide a safe, secure and reliable water supply for consumers. To this end, the Australian Drinking Water Guidelines Framework for the Management of Drinking Water Quality (the ADWG Framework) outlines a comprehensive, integrated approach to ensure drinking water safety – where multiple barriers from ‘catchment to tap’ must be present in order to reduce the risk of contamination to consumers (NHMRCC 2011, WHO 2011). Under the guiding principles of the ADWG Framework, catchments are considered the

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primary barrier in the multi-barrier approach, therefore, suppliers of drinking water have a significant interest and role in catchment management.

In southeast Queensland (SEQ), more than 90% of the drinking water supply is sourced from 'open catchments', which are catchments that support numerous land uses including for agriculture, forestry, industry, recreation and residential. Development of catchment areas to accommodate these land uses has led to degradation of ecosystem services that help to provide clean water, while many of these land uses themselves result in point and diffuse pollution.

Wastewater from domestic onsite sewerage facilities (OSFs) contains numerous contaminants, including pathogenic microorganisms, synthetic chemicals and nutrients. While chemical pollutants are of concern, pathogenic microorganisms, such as bacteria, protozoa and viruses, are considered the greatest threat to drinking water safety (ADWG 2011). Numerous incidents have been documented worldwide where contamination of pathogenic organisms in drinking water has led to increased gastro-intestinal illnesses across communities, and in some cases has led to serious illness or death (Hrudey & Hrudey 2007). Additionally, the impacts of wastewater on stream ecosystems are varied and complex. Large loads of pathogens from anthropogenic sources can cause substantial changes in stream microbial communities, which can then have flow-on impacts to important ecosystem functions such as decomposition and respiration rates (Burdon et al. 2020, Mansfeldt et al. 2020).

Studies undertaken across Australia have confirmed high failure rates of OSF (Billington & Deere 2012), while in SEQ, the failure rate of OSFs can be as high as 70% (Ahmed et al. 2005). With a potentially high failure rate of OSF and the ongoing residential expansion outside seweraged areas in SEQ, this raises a large concern for how wastewater contamination impacts on water quality can be managed, aquatic environments can be protected and drinking water safety assured. In order to address the risks to source water quality posed by poorly sited or failing OSF, catchment managers apply on-ground interventions including rehabilitation/revegetation of riparian zones, installation of vegetative buffers, replacement of unsuitable OSF or establish connections to nearby reticulated sewage networks (Billington & Deere 2012, Akunna et al. 2017). However, catchment managers face considerable challenges regarding best location for investment and which type of on-ground catchment projects will deliver the greatest benefit to water quality. This raises the question of where and how do we invest across large catchment areas with multiple high risks when budgets and resources are limited?

Identifying the sources of risks and understanding their impacts on water quality is essential for developing on-ground catchment project plans. Baker et al. (2016) developed a standardized survey method for assessing catchment microbial loads and therefore risk to water quality from both diffuse and point sources from six types of hazardous processes. However, the sanitary survey method has been primarily carried out with field visits to pre-determined sites deemed to be of potential sanitary significance. As resources are always limited and only a small selection of sites can be visited, this approach can only give the level of risk posed by the hazardous processes from a portion of the catchment and may not be representative of larger catchment area. With the increased accessibility of geospatial information such as topography, land use, vegetation etc., many field-based surveys can now be applied to large areas using desktop analysis (Oosting & Joy 2011, Dubber et al. 2014). Therefore, the remote desktop application of the sanitary survey may provide a more comprehensive representation of catchment risks to water quality.

Prioritizing interventions across catchments is essential when only limited resources are available. Information from assessments such as the sanitary survey has to be integrated into a structured, transparent and repeatable framework in order for the prioritization approach to be robust. The Catchment Investment Decision Support System (CIDSS) is an approach developed by Seqwater and Truii Pty Ltd that combines model and survey data of catchment hazardous processes to water quality using a risk framework. The CIDSS allows for the spatial optimisation of interventions to be applied to reduce the highest risks to a downstream endpoint (i.e. the raw water intake for a drinking Water Treatment Plant (WTP)) based on intervention cost, efficacy and connectivity between the source and the WTP (see Thompson et al. 2021).

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The aim of this work is to assess the desk-top application of the sanitary survey method in combination with the Catchment Decision Support System to (1) estimate total daily loads of potentially pathogenic microorganisms arising from OSFs and the level of risk to adjacent streams and water received at a WTP, and (2) to develop an optimised catchment intervention program to reduce loads of potentially pathogenic microorganisms entering waterways in southeast QLD.

Methods

Study Area

The Sanitary Survey method and development of an intervention portfolio by the CIDSS is being applied across Seqwater's ~1.8 million ha of source catchments in southeast Queensland, Australia. The region has a subtropical climate with average summer and winter temperatures of 24 °C and 14 °C respectively. Annual and seasonal rainfall are variable with most rainfall occurring in summer and autumn. River discharge regimes have very high hydrological variability (Thompson et al., 2016). Seqwater owns <5% the catchment area which is primarily around dams, while approximately 70% of the catchments is used for agriculture, dominated by livestock industries, and only 22% of the source catchments remains as natural environment. The catchments also include urban, peri-urban and rural development where wastewater treatment systems vary from primary and advanced secondary OSFs to high-capacity reticulated sewage mains with treatment at municipal sewage treatment plants (<https://www.data.qld.gov.au/dataset/land-use-mapping-series>).

This paper focuses on the Canungra Creek catchment which is located within the Logan-Albert basin. The catchment area totals 92 km² and comprises public lands for nature conservation in the headwaters, livestock grazing in the mid to lower-catchment, and rural-residential areas and peri-urban development in the lower catchment. Canungra Creek provides source water to a water treatment plant (WTP) which provides drinking water for the township of Canungra, with a population of 1,229 people but current population growth is on average 2% per year (<http://www.qgso.qld.gov.au>). Canungra is serviced by a small sewage treatment plant, no significant sewer infrastructure outside of the main township. While pathogen sources from livestock industries, stormwater outlets and informal water-based recreation are present and may contribute to water quality risks at the WTP, this paper focuses just on OSF sources. It is assumed the OSFs in this catchment are conventional septic tank-soil absorption trench systems. Furthermore, the OSFs are evaluated and interventions applied under two scenarios: (1) all the septic tank systems are experiencing hydraulic failure (worse but not unrealistic case) and (2) the septic systems are functioning normally.

Application of Sanitary Survey

To estimate the current water quality impacts of OSFs, Seqwater co-developed a methodology in collaboration with colleagues in other parts of the water services sector (Baker et al. 2016). Details of the steps are outlined below,

1. Identify sites

Identification of OSFs was through desktop analysis using publicly available imagery, cadastre data (<https://hub.arcgis.com/datasets/esriau-localgovt::queensland-cadastre?geometry=105.520%2C-26.424%2C-174.017%2C-11.945>) and sewerage line layers (obtained from relevant utilities in SEQLD). An OSF was assumed to be located on a property if the Lot was not adjacent to a sewer line. Only a single OSF was assumed to be located on a single Lot unless it was visually obvious using the spatial imagery that the Lot had been subdivided and there was more than one OSF present. If the exact location of the OSF in the Lot could not be easily identified visually, then the location was assumed to be in the centre of the Lot.

2. Calculate likelihood

The likelihood of pathogen contamination entering the waterway from each OSF site is established by evaluating the potential connectivity of the OSF to the stream network. This considers the slope and proximity of OSF to a stream (orders 3 – 8), and the efficacy of the treatment system. Two datasets were

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created, one that assumed all OSFs were functioning correctly and one that assumed all OSFs had hydraulic failure (see Baker et al. 2016 for further details regarding hydraulic failure and likelihood matrix).

3. Calculate consequence

The consequence scores are logarithmic values based on literature (Ferguson & Kay 2012) estimates of mean concentrations, and are used to generate an *E. coli* score and a protozoa score. Following Baker et al. (2016) all OSFs were assumed to service 10 people or less and thus have 'raw' consequence scores of 8 for *E. coli* and 4 for protozoa. Adjustments were made if there are any mitigation measures present to derive a 'modified' consequence score. Mitigation measures include the presence of a secondary treatment system in the OSF, chlorination, and/or a buffer zone of 50m between the land irrigation area and the nearest waterway.

4. Site risk score

Risk at an individual site is reported as a modified risk score (a logarithmic value of the mean daily pathogen load), which is calculated as: Modified risk = Modified Consequence – (5 – Likelihood)

Catchment Investment Decision Support System

The CIDSS is a planning support tool that evaluates hazardous processes and quantifies their contribution to total suspended sediment (TSS) and/or pathogen loads within source water received at downstream WTPs. Deposition and trapping of sediment and attenuation of pathogens along the transport pathways are explicitly included. The contribution from each of the hazardous processes to the overall TSS and pathogen loads are then assessed as the level of risk to consumers, which is based on the WTP treatment capability. A simulated annealing optimiser is then used to produce a portfolio of intervention activities (from a list of 63 different intervention activities with individual efficacies) across a given source water catchment area and is designed to provide the greatest reduction in drinking water quality risk for a given budget. The input hazards and solution interventions are specified at hydro-geomorphic units representing source water subcatchments containing similar land use and therefore processes generating hazards to water quality. These base spatial units are referred to as planning units (PUs) and are typically 14 ha to 4000 ha (25th–75th percentile). The Canungra Creek catchment is only made up of four planning units which range in size from 785 to 4546 ha. Further details regarding the CIDSS framework and computational steps see Thompson et al. (2021).

Once all OSFs in the Canungra Creek catchment were identified and had modified risk scores assigned to them, the data was incorporated into the CIDSS to estimate the total pathogen loads from the PU and also reaching the downstream WTP. The example scenario was designed to reduce the pathogen load from OSFs therefore the only intervention applied was OSF upgrade from conventional septic tank-soil absorption trench systems to secondary aerated wastewater systems with disinfection prior to irrigation. The CIDSS hazard weightings are split between bacteria and protozoa (see Thompson et al. 2021).

Table 1. Canungra WTP treatment capability thresholds.

Description	Risk level	Bacteria (log ₁₀ organisms/day)	Protozoa (log ₁₀ organisms/day)
Minor	2	4	4
Moderate	3	5	5
Major	4	6	6
Catastrophic	5	8	8

Results and Discussion

Presence of OSFs

Desk-top mapping identified over 42,000 OSFs across drinking water source catchments in SEQ, with 215 OSFs present in the Canungra Creek catchment. It has been stated that over one million OSFs are present across Australia, with over 300,000 OSFs located in New South Wales (NSW) which has an area of 80M ha (Greary & Lucas 2019).

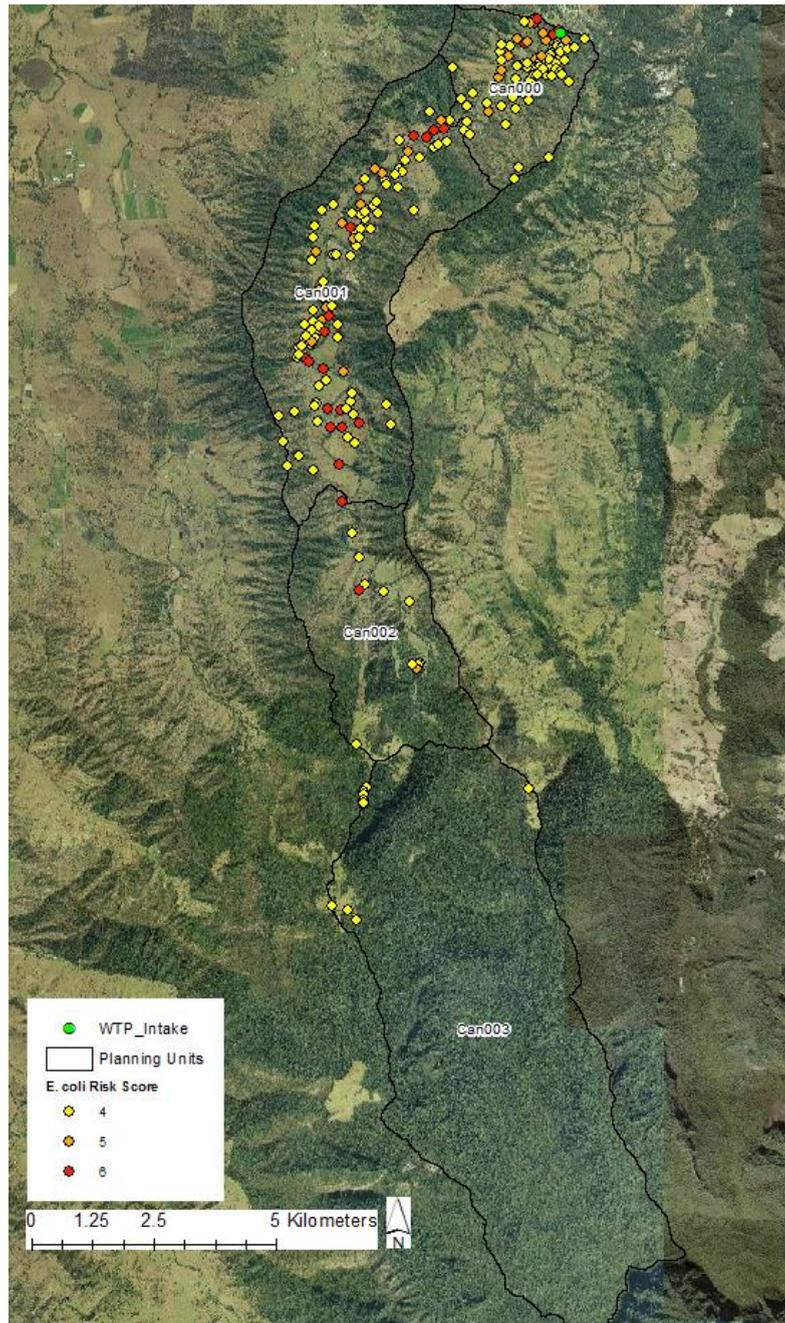


Figure 1. Location and modified risk scores of all OSFs across the Canungra catchment.

A total of 55 of the 215 OSFs were located within 100m of a watercourse and therefore have an almost certain likelihood of wastewater connecting to a watercourse if an hydraulic failure occurs. Based on the modelled assumption that these systems are not functioning correctly and after accounting for pathogen attenuation between the sources and the WTP, the risk from 24 of the OSFs can be considered extreme with potential daily *E. coli* loads of 6 log and protozoa loads of 2 log per OSF. Another 31 OSFs could also be considered high risk with potential daily *E. coli* load of 5 log and protozoa loads of 1 log.

Under the second scenario of all OSFs functioning normally, the likelihood of contamination is reduced to likely for those OSFs within 50m and unlikely for those OSFs between 50 and 100m from the waterway (Baker et al. 2016). Oosting and Joy (2011) found that soil type, groundwater intrinsic susceptibility (aquifer potential for groundwater contamination from surface contamination) and system age were the greatest contributors to overall risk of OSF contamination to water quality in Ontario. The study did not use a typical likelihood and consequence matrix to determine risk, instead, each of the nine selected parameters was

assigned a risk score value and a weight based on its importance and the certainty of the data (Oosting & Joy 2011). Other studies in Australia have found that soil type surrounding the OSF is a major contributing factor to likelihood of contamination, due to the performance of the soil sorption system (Carroll et al. 2006, Geary & Lucas 2019). The sanitary survey method considers soil type for OSFs that only have surface effluent drainage which is likely to occur in OSFs with secondary treatment. However, because we have assumed the current OSFs identified through the desktop mapping are older OSFs with sub-surface drainage, soil type is not considered for these systems, however depth to bedrock and grain size is used to estimate likelihood for advanced OSFs (Baker et al. 2016). Soil type is ideally required at the site scale, however a geospatial layer of this resolution is not available for southeast Queensland, therefore proximity to waterway is likely to be the next best parameter to use in determining likelihood of contamination from OSFs (Geary & Lucas 2019).

Pathogen Load Reduction and Impact

The CIDSS scenario showed that reduction of total daily pathogen loads could be achieved via upgrade of 52 OSFs within 100m of the watercourse from conventional septic tank-soil absorption trench systems to secondary aerated wastewater systems with disinfection prior to surface irrigation (Table 2 and 3). Having the secondary/disinfection systems in place means that the pathogen load can be partially treated before the effluent is released, therefore if there is a hydraulic failure (e.g. soil saturation or heavy rainfall event) then the consequence of contamination will be comparatively reduced (Baker et al. 2016).

Table 2. Total reduction in pathogen loads at the Canungra WTP before and after intervention.

Scenario	BEFORE <i>E. coli</i> (log ₁₀ organisms/day)	AFTER <i>E. coli</i> (log ₁₀ organisms/day)	BEFORE Protozoa (log ₁₀ oocysts/day)	AFTER Protozoa (log ₁₀ oocysts/day)
100% Failing OSF	7.1	6.1	3.1	2.1
Normal Function OSF	6.0	4.1	2.0	<1.0

Under the scenario where all the OSFs are functioning normally, upgrades from basic to advanced systems means that the minimum base load of *E. coli* that can be achieved with the present number of OSFs across the catchment is 4.1 log while protozoa can be eliminated as a threat (Table 2). This could also be interpreted as there being up to a 2.0 log difference in pathogen load depending on whether the OSFs are functioning correctly or not, and therefore provides upper and lower bounds of the potential pathogen load, which is important for understanding potential loads given the lack of information available in regards to OSF function and maintenance (Carroll et al. 2006).

In terms of how this load reduction impacts water received at the WTP, the categories of risk used in the CIDSS relate to the capability of the WTP to adequately treat the pathogen concentrations present in the raw water (Table 1). The treatment capability of the Canungra WTP is extremely compromised when *E. coli* and protozoa loads reach 8.0 log and majorly compromised when the loads reach 6.0 log (Table 1) which has potential to cause disease burden within the community (WSAA, 2015). Although the *E. coli* load after intervention was predicted to be 6.0 log if the OSFs were upgraded but still failing, this would still be considered a major impact on WTP capability, however, it does show a considerable improvement as the before intervention pathogen impacts were approaching an extreme impact. If the 52 OSFs were functioning correctly but still upgraded the pathogen load would change from having a major impact to a moderate impact to WTP capability, as the *E. coli* load would be reduced to 4.1 log. This indicates the importance of both upgrading OSF treatment systems and ensuring that they are being maintained and functioning.

Domestic wastewater inputs to streams have been shown to result in > 50% of the bacterial community DNA arising which has caused an impact on aquatic biodiversity by increasing the relative abundance of bacteria from human gut microbial taxa (Mansfeldt et al. 2020). These changes in community together with other wastewater components such as nutrients and micropollutants, can lead to changes in ecosystem metabolism (e.g. rates of primary productivity vs rates of community respiration) and increase organic matter

decomposition rates, which could ultimately lead to greater carbon release from the aquatic environment (Burdon et al. 2020). While this assessment estimates the potential pathogen load from OSFs to Canungra Creek, further studies would need to take place to determine whether these loads are enough to cause a shift in microbial community or ecosystem metabolic processes within the creek.

Spatial Analysis and Project Implementation

The total daily load of *E. coli* from OSFs that could be exported from each of the four PUs (before intervention) ranged from 5.0 log to 7.3 log. Accounting for attenuation in transport between each PU and the WTP, *E. coli* loads are reduced to between 2.3 log to 6.9 log across the PUs. The highest unattenuated load was from the Can001 PU, second closest to the WTP intake (Figure 1). However once attenuated, the Can000 PU immediately upstream of the WTP intake contributed the highest load. This shows the importance of determining the spatial location of the OSFs and accounting for longitudinal processing (die-off) of pathogens once exported from the site, so that the potential impacts from pathogen loads generated in different parts of catchment can be understood relative to each other (Hamilton et al. 2018).

Table 3. Total number and cost of OSF upgrades for each PU and total reduction in pathogen loads to downstream surface water at the Canungra WTP, assuming 100% of OSFs are not functioning.

Planning Unit	Reduction in <i>E. coli</i> (log ₁₀ organisms/day)	Reduction in protozoa (log ₁₀ oocytes/day)	No. of OSF upgrades	Total cost
Can000	2	1.8	20	\$299,999
Can001	2	1.7	30	\$350,000
Can002	2	1.0	2	\$29,999
Can003	0	0	0	\$0
Total			52	\$779,998

Accounting for the longitudinal processing and understanding the difference in pathogen loads before and after interventions applied at the planning unit scale allows for OSF upgrades to be prioritized by PU. This is through ranking the PUs according to the reduction in total daily loads before and after intervention so that the PU with the largest reduction in pathogen load will be ranked first (Thompson et al. 2021). While this may appear trivial for a single small catchment like Canungra, the source catchments across SEQ are discretized into 1450 PUs and can now be prioritized for rolling out a program of intervention portfolios to target areas of greatest risk to drinking water quality, hence public health. The mapping outputs showing the locations of priority PUs and OSFs provides a planning guide for catchment managers, although this has to be considered alongside accessibility and landholder willingness. Past OSF upgrades have been dependent on random audits by council officers and/or the landholder’s willingness, which potentially (likely) means the highest risk OSFs are not included, therefore the prioritization approach means that these OSFs are included and ensures a more cost-effective process.

Conclusions

The desk-top application of the sanitary survey method was able to identify OSFs which were likely to contribute to pathogen contamination to surface water. Given the lack of information available in regards to OSF function and maintenance, this assessment provides an estimated range of pathogen loads that could reach the WTP, which can help guide future planning in relation to risk to WTP operations. Although estimating the pathogen loads from wastewater allows for an understanding of whether there may be potential impacts to the stream ecosystem, further investigation is needed to determine any changes in downstream microbial communities or ecosystem metabolism. However, the assessment could still be applied in other locations, in order to rank streams that may be impacted by wastewater arising from OSFs.

Applying the optimization component within the CIDSS and ranking PUs by the potential reduction in pathogens allowed for an in-catchment intervention program targeting high risk OSFs to be developed, which will facilitate a more cost-effective process for auditing OSFs, and identifying which OSFs are required to be upgraded and/or important to maintain in order to reduce pathogen loads that reach the stream.

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