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Standardised survey method for identifying catchment risks to water quality

D. L. Baker, C. M. Ferguson, P. Chier, M. Warnecke and A. Watkinson

ABSTRACT

This paper describes the development and application of a systematic methodology to identify and quantify risks in drinking water and recreational catchments. The methodology assesses microbial and chemical contaminants from both diffuse and point sources within a catchment using *Escherichia coli*, protozoan pathogens and chemicals (including fuel and pesticides) as index contaminants. Hazard source information is gathered by a defined sanitary survey process involving use of a software tool which groups hazards into six types: sewage infrastructure, on-site sewage systems, industrial, stormwater, agriculture and recreational sites. The survey estimates the likelihood of the site affecting catchment water quality, and the potential consequences, enabling the calculation of risk for individual sites. These risks are integrated to calculate a cumulative risk for each sub-catchment and the whole catchment. The cumulative risks process accounts for the proportion of potential input sources surveyed and for transfer of contaminants from upstream to downstream sub-catchments. The output risk matrices show the relative risk sources for each of the index contaminants, highlighting those with the greatest impact on water quality at a sub-catchment and catchment level. Verification of the sanitary survey assessments and prioritisation is achieved by comparison with water quality data and microbial source tracking.

Key words | catchment, chemicals, pathogens, quantitative microbial risk assessment (QMRA), risk, sanitary survey

D. L. Baker (corresponding author)
C. M. Ferguson
P. Chier
M. Warnecke
GHD Pty Ltd,
Level 6, 20 Smith St,
Parramatta,
New South Wales 2150,
Australia
E-mail: *Danielle.Baker@ghd.com*

A. Watkinson
Seqwater,
PO Box 16146, City East,
Brisbane,
Queensland 4002,
Australia

ABBREVIATIONS

A list of terms and abbreviations used in the text.

Chemical score	A logarithmic scoring of a particular chemical hazard, which is then modified for mitigating factors. This is used to calculate the consequence rating for an individual site.
Consequence rating	The effect of the hazard to catchment water quality, on a scale of Insignificant – Minor – Moderate – Major – Catastrophic (numerically 1 through to 5). This applies to an individual site, unless specified as otherwise.
Consequence score	Calculated for a specific hazard (*E. coli*, protozoa or chemical). The consequence score is then used to calculate the consequence rating for an individual site.
Cumulative risk	The combined risk from sites within a sub-catchment or catchment. This is performed by combining the individual site consequence scores, which are modified for likelihood, and is further modified for attenuation of upstream hazards.

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Cumulative risk score	The combined modified risk scores (MRSs) of sites of one site type, for each hazard. The MRSs are not added arithmetically (e.g. $x + y$) but logarithmically (e.g. $\log(10^x + 10^y)$.
Cumulative risk rating	The rating calculated from the cumulative risk score of a catchment, describing the risk of the hazard from combined sites of one type to catchment water quality, on a scale of Very low – Low – Medium – High – Very High (numerically 1 through to 5).
Decentralised system	A sewage treatment system with an approximate capacity of 100 EP.
E. coli score	A number derived from the logarithm of the load of *E. coli* expected in a particular hazard, which is then modified for mitigating factors. This is used to calculate the consequence rating for an individual site.
Hazard	In this instance, a potential threat to catchment water quality from an *E. coli*, protozoa or chemical hazard.
Individual site risk	The risk assigned to an individual site, calculated from the likelihood rating and consequence rating.
Likelihood rating	The likelihood of the hazard affecting catchment water quality, on a scale of Rare – Unlikely – Possible – Likely – Almost Certain (numerically 1 through to 5). This applies to an individual site, unless specified otherwise.
MRS	Used in the calculation of the cumulative risk from the characteristics of the surveyed individual sites. The MRS is calculated for each hazard at each site. Defined as the *Consequence score – (5 – Likelihood score)*.
Module	The assessment procedure for a single hazard input source. Six modules are used – Sewage treatment plant (STP), On-site, Industrial, Agricultural, Stormwater, and Recreational.
On-site system	A small sewage treatment system, designed with an approximate capacity of 10 EP.
Protozoa score	A number derived from the logarithm of the load of *Giardia* expected in a particular hazard, which is then modified for mitigating factors. This is used to calculate the consequence rating for an individual site.
Risk rating	The risk of the hazard to catchment water quality, on a scale of Very low – Low – Medium – High – Very High (numerically 1 through to 5). This applies to an individual site, unless specified as otherwise.
Risk score	Calculated by addition of the likelihood rating and the consequence rating. This is then used to generate the risk rating.
Site	A location assessed for one or more hazards to catchment water quality.
Site type	One of six groupings of sites used in this methodology (STP, On-site, Industrial, Agricultural, Stormwater, and Recreational).
SPS	Sewer pumping station.
Survey completion estimate	Defined as the proportion of sites of one type which were assessed in the survey, as a percentage.
Upstream site	The cumulative risk scores from an upstream sub-catchment, presenting an additional potential contamination input to a downstream sub-catchment. This risk score is attenuated in some circumstances to account for processes which can reduce risk.

INTRODUCTION

Proactive management of drinking water supplies is promoted by the World Health Organization (WHO) and the

Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) and emphasises a multi-barrier approach to minimising risk of contamination to drinking water supplies (WHO 2011). The use of a Water Safety Plan to identify and control risks to water supplies highlights the importance of understanding the characteristics of the water catchment and identifying the hazards that can impact water quality (WHO 2009). This paper presents a systematic approach to the detection of those hazards.

Existing guidance for the detection of hazards and the evaluation of potential risks were reviewed (WHO 1997, 2009; Water Services Association of Australia (WSAA) 2003; NHMRC 2008), and a systematic methodology developed to identify and quantify water quality risks to (1) drinking water supplies and (2) recreational users. The outputs support an improved knowledge of both diffuse and point sources within a catchment and can be used to quantify and compare the water quality risks from these sources, both within and between water catchment areas. The methodology has been developed to facilitate the integration of the outputs into a broader quantitative microbial risk assessment (QMRA) framework to support the calculation of health-based targets for drinking water supplies.

METHOD

The methodology describes a planned and systematic approach to the collection and analysis of catchment information to assess likelihoods, consequence and subsequent risks for six types of source hazards frequently found within surface and groundwater catchments. These include: sewage treatment plants (STPs) (>100 estimated persons, EP) and sewage infrastructure; on-site systems (<100 EP); industrial activities; agriculture; stormwater; and recreational sites. The information collection fields for these hazards are incorporated into the tool under separate modules.

The methodology is focused on the assessment of three potential contaminant classes of pollutants that can frequently occur in water catchments, as represented by index contaminants. *Escherichia coli* is included as an index of chlorine sensitive microorganisms. Protozoan pathogens are included as an index of chlorine resistant microorganisms. Chemical contaminants (including pesticides, herbicides and fuels) represent the third index. Ultimately the source hazards are evaluated for each site by the module type and the three index contaminants considered, prior to the calculation and verification of catchment risk.

The sanitary survey process is broken into a number of discrete steps that together support an understanding of sanitary risk in the catchment. These steps are site identification, field survey, the calculation of likelihood, consequence and risk for the individual surveyed sites, the calculation of the cumulative risk for the sub-catchments and overall catchment, and the verification of this cumulative risk. The methodology steps are shown in Figure 1.

Identify sites

The first step in applying the sanitary survey methodology is to identify the sites that need to be investigated. Both the NHMRC (2008) and Water Services Association of Australia (WSAA) (2003) guidelines describe the potential sources of contamination that should be inspected including: municipal and decentralised wastewater discharges; recreational and bathing locations; on-site systems; urban stormwater; farming, native animals and industry.

To guide site selection, a series of questions was developed to identify and characterise sites deemed to be of potential sanitary significance (Table 1). The process outlined in Figure 1 is applied in consultation with experienced catchment officers and identified stakeholders, including councils, using information from existing studies, geospatial information, and by taking into account accessibility and the scale of the potential risk. The primary consideration in site selection is to target potential hazard sites for point and diffuse faecal or chemical contamination through discharge and rainfall mobilised mechanisms. Where there is a large number of a particular type of site within a catchment (e.g. on-site systems), a sub-sample of sites is selected to provide a practical snapshot of the risk posed by these systems to the catchment. Particular effort is made to capture every large point discharge in a catchment, since by volume these are considered the highest sanitary risk practices. Once identified, sites are scheduled for survey.

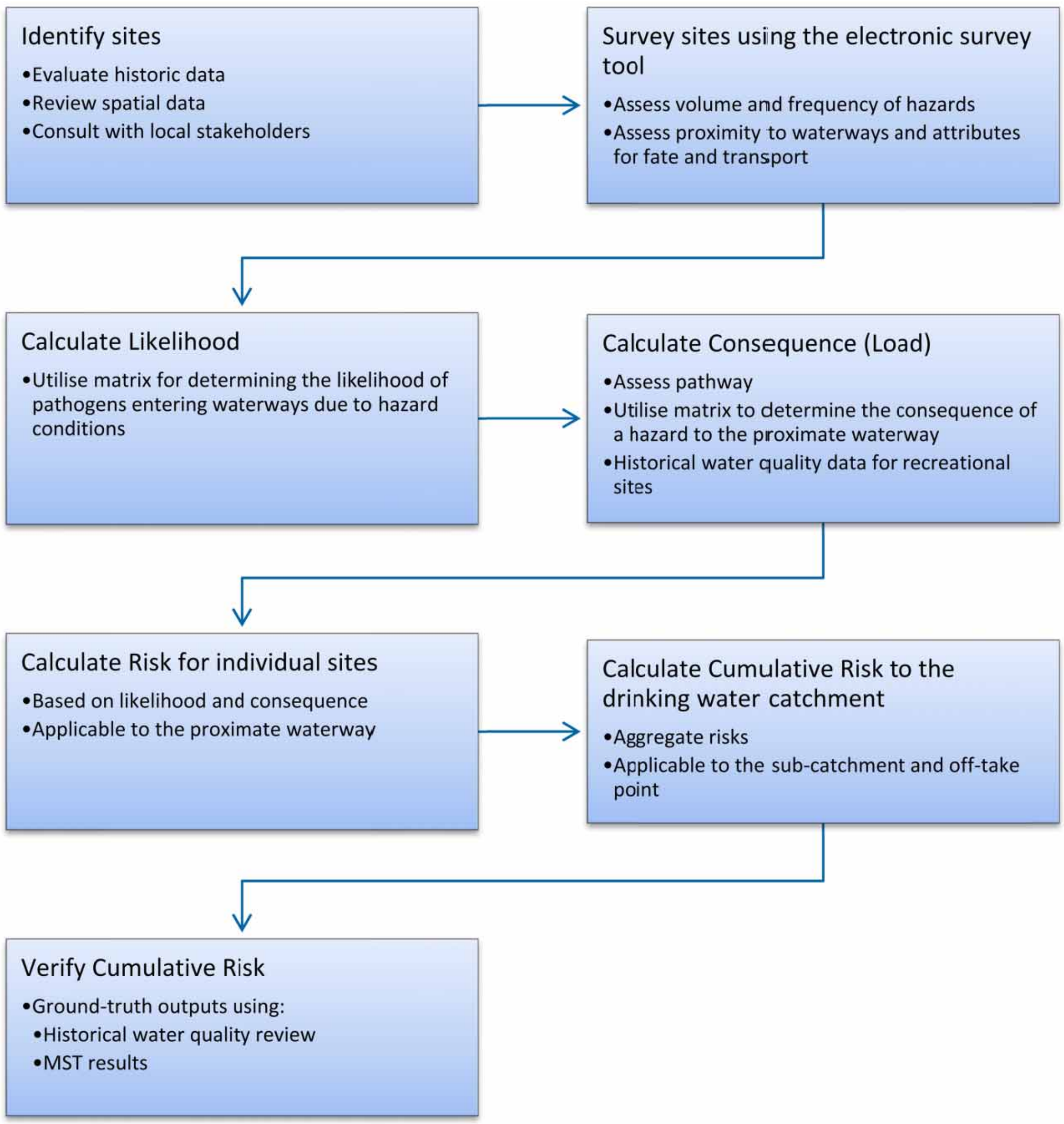

Figure 1 | Methodology for estimating risk to drinking water supplies.

Survey sites

An electronic sanitary survey software tool was designed to aid in the collection of survey data for field sites. The primary purpose of the tool is to collect information on the location, volume and frequency of the occurrence of pollution and to assess the proximity of these sources to waterways. This proximity is of paramount importance in determining the likelihood that source material will be transported to the waterway and to subsequent downstream locations. Site surveys to collect historical and operational information involve a visual inspection of premises or activities, and an interview with the owner, manager or service technician in the case of on-site systems. Where a site cannot be accessed for survey, estimated volumes and load values are used as a default to assess likelihood of contaminant sources.

An array of information fields are captured to help determine the likelihood and risk through the use of standardised matrices. These likelihood and consequence tables list the

Table 1 | Decision framework for site identification and evaluation

No.	Question	Action
1	Does the site have an STP with >100 EP?	If yes – use STP module and proceed to Q3. If no – proceed to next question
2	Does the site have on-site sewage systems for <100 EP?	If yes – use on-site module and proceed to Q3. If no – proceed to next question
3	Does the site have an industrial or manufacturing process and produce a discharge?	If yes – use the industrial module and proceed to Q4. If no – proceed to next question
4	Does the site include agricultural activities?	If yes – use the agricultural module and proceed to Q5. If no – proceed to next question
5	Is there any evidence of stormwater runoff* or storage of chemicals or fuel?	If yes – use stormwater module and proceed to Q6. If no – proceed to next question
6	Is there any evidence of recreational water use?	If yes – use the recreational sites module. If no – why are you considering this site? Discuss contamination concern with local catchment officer.

*Stormwater is defined as 'rainwater that runs off all urban surfaces such as roofs, pavements, car parks, roads, gardens and vegetated open spaces' (Natural Resource Management Ministerial Council, Environment Protection and Heritage Council *et al.* (NHMRC & NRMMC 2011)).

collected survey information fields and are provided in the following sections. The field surveys and the resulting calculation and combination of likelihoods and consequences enable the determination of risks.

Calculate likelihood

The likelihood of faecal or chemical contamination entering the waterway at a given location is established from the collected data by evaluating the generation of contaminants and the potential connectivity, mitigated by the factors which can moderate or prevent contamination entering catchment waterways. A likelihood rating of rare, unlikely, possible, likely or almost certain is assigned. Likelihood assessments for each site are determined for any of the six hazard types using a matrix specific to that hazard. The spatial distribution of likelihood for each hazard informs an understanding of the dominant pollution sources across the catchment.

STP asset hazards

Within drinking water catchments, all STPs discharging to the environment represent a likely potential source of contaminants to waterways due to the volume of pollutants, particularly pathogens, in the source material. Wastewater systems that receive >20,000 L per day or 100 EP are considered as STPs and therefore likely sources. The likelihood of an STP impacting on a waterway is primarily determined by whether or not the STP has a direct discharge. The impact can be mitigated by the method of disposal, dilution of the discharge in the receiving water, improved treatment, increased buffer capacity and land disposal – increased the distance of discharge from the waterway (see Table 2). STPs that recycle water are still considered high risk, dependent on the pathogen reduction capacity of the systems, due to the potential for overflows and biosolids handling at the sites. The day to day impact of effluent recycling systems in the catchment is likely to be less where there is no direct discharge to waterways, or there is application of advanced treated effluent to land areas not proximate to waterways.

Other STP assets such as sewer pumping stations (SPS) are also evaluated with this module to account for the risk from sewer overflows. The likelihood of an effect from these assets is rated as an indirect discharge, modified by the distance from the asset to a receiving waterway and the potential frequency of overflow or failure.

Table 2 | Matrix of likelihood for contaminants entering waterways from STPs

Primary hazard*	Indirect discharge Water course >100 m	Indirect discharge Water course 50–100 m	Indirect discharge Water course <50 m	Direct effluent discharge
Microbial hazards	Unlikely	Possible	Likely	Almost certain
Hazardous chemicals	Unlikely	Possible	Possible	Almost certain

*If hydraulic failure is evident or compromised during rainfall events, treat as direct effluent discharge.

Chemicals, such as chlorine and chlorine-based disinfectants, are often used at STPs. Therefore, the likelihood of chemical hazards is evaluated based on the primary hazard – 'Hazardous chemicals' in Table 2. If there are no chemical hazards on site, the likelihood would be set to 'rare'.

On-site system hazards

This module estimates the likely impact of on-site and decentralised systems (<100 EP). Critical to this assessment is the determination of lot sizes less than two hectares which can have a cumulative impact in small clusters. Forty hectares is considered a benchmark with regard to density of on-site systems in peri-urban areas (Franklin 2011) for drinking water catchment subdivisions. For the likelihood classification of on-site systems, the focus is placed on the determination of the individual system as a point source risk. Factors that can contribute to the presence and transport of pathogens from on-site systems include the proximity and type of watercourse (ephemeral, intermittent, dry drainage line); land slope; vegetative cover; type and function of the application system; soil type and geomorphology; size of the application area; treatment system function; system users; rainfall; and soil saturation.

Ease of transport of pathogens (surface flow versus subsurface flow) is the highest-weighted component in determining the likelihood of contamination. Efficacy of the treatment system is weighted as the second-highest factor. In this context, a treatment system failure is regarded as equipment not functioning within the treatment tank, such as disinfection not occurring or a blower failure. Hydraulic failure describes overloading of systems; application area failures; improper dispersal such as release from the end of a hose without a sprinkler; or visible pooling of effluent. Other factors contributing to, or mitigating transport and the concentration of contaminants present, are also considered as secondary factors contributing to likelihood ranking, specifically soil type and slope (see Table 3).

Chemical hazards are not expected to be present at sites with on-site treatment systems. Therefore, the likelihood of this hazard is considered 'rare'.

Table 3 | Matrix of likelihood for contaminants entering waterways from on-site systems

Primary hazard	Secondary hazards	Watercourse >100 m	Watercourse 50–100 m	Watercourse <50 m
Surface effluent irrigation	Hydraulic failure* Steep slope**	Likely	Almost certain	Almost certain
	Hydraulic failure* Moderate slope or Flat	Possible	Likely	Almost certain
	Normal function steep slope** Sand, Rock or Clay	Possible	Likely	Almost certain
	Normal function steep slope** Loam or Clay/Loam	Possible	Possible	Likely
	Normal function Moderate slope or Flat Loam or Clay/Loam	Rare	Unlikely	Likely
	Normal function Moderate slope or Flat Sand, Rock or Clay	Unlikely	Possible	Likely
Sub-surface effluent irrigation	Hydraulic failure*	Likely	Almost certain	Almost certain
	Normal function	Rare	Unlikely	Likely
No effluent irrigation***	Hydraulic failure* Steep slope**	Likely	Almost certain	Almost certain
	Hydraulic failure* Moderate slope or Flat	Possible	Likely	Almost certain
	Normal function	Rare	Unlikely	Possible

*Hydraulic failure = overflow of effluent.
**Steep slope = greater than 10% slope. A moderate slope is regarded as 5–10% slope.
***No effluent irrigation = either pumped out and removed from catchment or to a treatment facility.

Industrial hazards

Manufacturing facilities including water treatment plants (WTPs) and large industrial sites are assessed using the industrial source hazards module (Table 4) and the stormwater hazard module (see Table 6). An industrial discharge is considered as a point source of contamination. To this end the process is considered 'wet' and will involve the daily or routine generation of trade wastewater. This may occur during the processing itself or through wash down activities. Manufacturing and industrial sites that do not generate wastewater are considered 'dry'. These sites are to be assessed using the stormwater module, since stormwater is the most probable mechanism by which the microbial or chemical contaminants from these sites can be discharged to waterways.

With respect to pathogens, high hazard industrial discharges are 'wet' activities that involve faecal material (including dairy wash down), animal parts (including abattoirs), raw materials of animal origin (including dairy and meat manufacture and fertiliser manufacture), WTP supernatant and rendering. Low pathogen hazard industrial discharges include raw materials of agricultural origin such as fruit and vegetable processing.

High hazard chemical discharges are 'wet' activities that involve toxic chemicals, a large amount of chemicals or fuels in their processes e.g. paper manufacture and landfill leachate discharge. Low chemical hazard industrial discharges are 'wet' activities that are either small in scale or the chemicals used in the process are low toxicity or diluted. Examples include mechanical workshops with car and parts wash bays, and car washes.

All industrial facilities with discharge direct to waterways are considered almost certain for high hazard or likely for low hazard to be a source of contaminants. The likelihood of contaminant transport to waterways via indirect discharge or overland transport decreases with increasing distance from the waterway (Table 4).

Table 4 | Matrix of likelihood for contaminants entering waterways from industrial sites

Primary hazard	Water course >100 m	Water course 50–100 m	Water course <50 m	Direct discharge
High hazard process	Unlikely	Possible	Likely	Almost certain
Low hazard process	Rare	Unlikely	Possible	Likely

Agriculture

A number of factors determine the likelihood of contaminant contributions from agricultural activities. Primary factors include the intensity of animal husbandry, the use of biosolids and application of chemicals. Agricultural activities often include the use of fertilisers, including biosolids, which can be a source of nutrient and pathogen pollution. The application of pesticides and herbicides is also a significant potential source of chemical contaminants. Secondary factors that can increase or decrease the likelihood of contaminants being transported to waterways include the slope, and frequency of use (Table 5).

Mitigation factors that reduce the transport of contaminants entering waterways include the fencing of riparian zones to prevent animal access and hence reduce direct faecal deposition to streams. The presence of a vegetated riparian buffer strip adjacent to the waterway provides significant removal and retardation of many pollutants.

Sites with the following attributes are defined as likely sources of agricultural hazards: direct animal access to waterways; intensive feed lots and dairies; broad scale grazing; and animal depositions (including piles of biosolids) within 50 m of intermittent or permanent waterways.

An additional complication for the assessment of diffuse inputs from agricultural sources is the dynamic nature of agricultural activities. This increases the uncertainty in determining whether animals are regularly present in locations where they are observed, and whether or not they have access to waterways. This variability is higher than the variability associated with fixed point sources such as sewer infrastructure. In situations where multiple types of animals are present at a site, the most numerous animal type is used for the purpose of the assessment.

Consequence and subsequent risk assessments are also affected by the uncertainty in animal activities. In particular, there can be significant variability in the severity of the consequence, for example pathogen prevalence, concentration and type associated with various animal faecal sources.

Table 5 | Matrix of likelihood for contaminants entering waterways from agriculture

Primary hazard	Secondary hazard***	Fenced watercourse >100 m	Fenced watercourse 50–100 m	Fenced buffered watercourse <50 m	Fenced un-buffered watercourse <50 m	Direct access to waterway
*Intensive animals	Steep slope	Unlikely	Possible	Likely	Almost certain	Almost certain
	Moderate or Flat slope	Unlikely	Unlikely	Possible	Likely	Almost certain
Broad scale animals	Steep slope	Unlikely	Unlikely	Possible	Likely	Likely
	Moderate or Flat slope	Rare	Unlikely	Unlikely	Possible	Likely
Biosolids**	Steep slope	Unlikely	Possible	Likely	Almost certain	**
	Moderate or Flat slope	Unlikely	Unlikely	Possible	Likely	**
Chemical & pesticide use	Frequent/High volume	Unlikely	Possible	Likely	Almost certain	**
	Infrequent/Low volume	Rare	Unlikely	Possible	Likely	**

*Intensive animal handling converts the pathway from a diffuse source to a point source, and so is categorised differently with respect to likelihood.
**Fencing does not apply to biosolids, chemical or pesticide use, although setback distance does.
***Steep slope defined as more than 10%, moderate as 5–10%.

Table 6 | Matrix of likelihood for contaminants entering waterways from stormwater sites

Primary hazard	*Advanced SW treatment	Stormwater detention (ponds)	Pervious surfaces without formal drainage	Stormwater drains	Kerb and gutter
Stormwater	Unlikely	Possible	Likely	Almost certain	Almost certain

*Advanced stormwater (SW) treatment includes wetland detention and proprietary *in situ* treatment devices such as rain gardens or filters.

The consequence evaluation is attributed based on the most dominant type of animal present at a site.

The likelihood of chemical and pesticide use on agricultural sites is evaluated in accordance with Table 5. In the case of a chemical or pesticide, if neither are used on site the likelihood would be 'rare'.

Stormwater hazards

A potential stormwater hazard occurs when pollutants could be carried to waterways via rainfall and surface runoff. This may happen on industrial sites or due to diffuse pollution from urban settlements. Industrial sites that do not generate wastewater and are considered 'dry' can store an array of chemicals and fuels used around the site, and this can constitute a stormwater hazard. Urban stormwater can present a pathogen, chemical or fuel hazard dependent upon the location and types of activities present to generate contaminants.

The likelihood is determined by the potential of contaminants to be transported from stormwater sites to the receiving waterway via overland runoff. Municipal stormwater infrastructure is very likely to transport runoff, having been designed for this purpose. Where pervious surfaces are involved, less transport can be expected. Where stormwater detention infrastructure is present, further reduced transport can be expected. This is reflected in the likelihood ratings assigned in Table 6.

Recreation

All sites where recreation includes immersion in the waterway (i.e. primary contact recreation) are considered as potentially almost certain sources of contamination to the drinking water supply. The potential shedding of pathogens and the accidental release of faecal contaminants in bathing areas are known hazards to water quality. Where immersion is less likely and brief, the likelihood has been rated as possible, or likely if toilet facilities are absent. This effectively applies to secondary contact recreation. At land-based recreation or passive recreation sites where contact with the water is unlikely, the likelihood of contaminants reaching the waterway is also rated as unlikely. However where passive recreation sites lack toilet facilities, the likelihood rating is increased to possible (see Table 7).

Chemical hazards are unlikely to be present at recreational sites. Therefore, the chemical likelihood has been set to 'rare' as a default. If chemicals are present, then the hazard evaluation should already be captured using the industrial module (refer to Table 1, Q. 3).

Calculate consequence

Once the likelihood of contamination reaching waterways is determined, the consequence of the contaminants on water quality is assessed for each individual site. A numerical consequence score is estimated for all contaminant types before being assigned a consequence rating, in accordance with Table 8.

For microbial contaminants, the consequence score is based on an estimated daily load of index microorganisms, which is used to generate an *E. coli* score and a protozoa score. Two scores are included to account for mitigation measures dependent on chlorination, which will reduce the consequence of chlorine-sensitive organisms such as *E. coli* to a much greater extent than for chlorine-insensitive organisms such as protozoa, and to account for the different concentrations of protozoa expected to originate from some groups of animals. The scores are logarithmic values based on literature (Ferguson 2005; Ferguson & Kay 2012) estimates of mean concentrations and are modified according to the scale of the hazard, mitigation measures such as wastewater treatment, and how effluent is released to the environment. Some mitigation measures which have been previously described as reducing the likelihood of contaminants reaching a waterway will also reduce the consequences of this should it happen, and this is reflected in the described score calculations.

Table 7 | Matrix of likelihood of contaminants entering waterways from recreational sites

Primary hazard	Toilet facilities available	Toilet facilities absent
Primary contact (immersion and child paddlers)	Almost certain	Almost certain
Secondary contact (minimal immersion and boating)	Possible	Likely
Passive recreation (no water contact)	Unlikely	Possible

Table 8 | Consequence ratings for microbial contaminant scores

Consequence rating	*E. coli* score	Protozoa score
Catastrophic	>9	6 or more
Major	>7	5
Moderate	>5	4
Minor	>3	3
Insignificant	3 or less	2 or less

For chemical contaminants, the consequence is determined in a similar way (Table 9). When the hazard is present, the consequences are rated, 'minor', 'moderate', or 'major', depending on the size of the source. These consequences are assigned a chemical score of 2, 3 or 4, respectively, for quantitative purposes. Where a chemical hazard is not identified, a chemical score of 1 (i.e. insignificant) is assigned.

Sewage systems

The consequence of all sewage structures and on-site systems are calculated using the following tables. The raw hazard is calculated from Table 10 and is described as an *E. coli* score and a protozoa score. The score is approximately equivalent to the logarithmic_{10} load of the organism generated per day based on literature values, but is simplified as a score for the tool. The mitigation measures applicable for a sewage system are then determined from Table 11. Finally, the modified scores (raw consequence reduced by mitigation measures) are compared to Table 8 to determine the overall consequence rating.

To account for the potential effect from SPS sites, the consequence is rated according to the estimated size of the upstream sewer system in Table 10, minus one, as discharge

Table 9 | Consequence ratings for chemical and fuel contaminants

Point source	Small source (<500 L or kg)	Large source (>500 L or kg)
Un-covered/un-bunded hazard	Moderate (3)	Major (4)
Covered/bunded hazard	Minor (2)	Moderate (3)

will be irregular and will not incorporate all flow from the sewer. The mitigation measures in Table 11 will not apply to SPS sites, with the possible exception of a 50 m buffer between the SPS and a receiving waterway.

Industrial consequences

For microbial contaminants, the raw hazard is calculated from Table 10 and is described as an *E. coli* score and a protozoa score. These scores are approximately equivalent to the logarithmic$_{10}$ load of the organism per day from literature values. The mitigation measures applicable for industrial 'wet' discharges are outlined in Table 11 and are described as modifiers to the scores from Table 10. The final score is then compared to the consequence ratings described in Table 8.

The consequences of any chemical contaminants in industrial 'wet' discharges are determined using the ratings assessment described in Table 9.

Agricultural consequences

The consequences from agricultural animal inputs are assessed in a similar manner to other faecal inputs. The input is treated as a point source on the property at a location where the animals are proximate to waterways, and the consequence is estimated using the expected load of microbial index organisms.

The raw hazard is calculated from Table 10 and is described as an *E. coli* score and a protozoa score. The score is calculated as 10% of the logarithmic$_{10}$ load of the *Giardia* cysts generated per animal per day derived from literature values. The score only includes 10% of the daily load as not all faecal material generated each day will be transported to a waterway and the overall score is scaled back to account for this. The mitigation measures applicable for the agricultural site are then calculated from Table 11 and

Table 10 | Raw consequence scores for microbial contaminants

Source	*E. coli* score*	Protozoa score
All sewage systems		
On-site system (10 EP or less)	8	4
Decentralised system (~100 EP)	9	5
Small municipal STP (~1,000 EP)	10	6
Large municipal STP (~10,000 EP)	11	7
Industrial sites		
High microbial hazard effluent, small flow (<3 kL/day)	9	4
High microbial hazard effluent, some flow (3–30 kL/day)	10	5
High microbial hazard effluent, large flow (>30 kL/day)	11	6
Low microbial hazard effluent, small flow (<3 kL/day)	2	1
Low microbial hazard effluent, some flow (3–30 kL/day)	3	2
Low microbial hazard effluent, large flow (>30 kL/day)	4	3
Agricultural animal sources		
Deer (1 animal)	8	5
Cattle (1 animal)	8	5
Sheep (1 animal)	9	3
Pigs (1 animal)	9	3
Horses (1 animal)	7	2
Birds (1 animal)	7	5
Other (1 animal)	7	2
Small herd size (10 animals)	+1	+1
Medium herd size (100 animals)	+2	+2
Large herd size (1,000 animals)	+3	+3
Juvenile animals present	+1	+1
Recreational sites		
Primary contact recreation (1 individual#)	6	3
Secondary contact recreation only (1 individual#)	4	1
Passive recreation (1 individual#)	2	−1
Low recreator numbers (10 individuals)	+1	+1
Medium recreator numbers (100 individuals)	+2	+2
High recreator numbers (1,000 individuals)	+3	+3

**E. coli* scores derived from Ferguson (2005), protozoa scores derived from Ferguson (2005) and Ferguson & Kay (2012).
#Individual per day.

Table 11 | Mitigation measures for microbial contaminants

Mitigation measure	*E. coli* score	Protozoa score
All sewage systems		
Secondary treatment	−2	−1
Chlorination	−3	0
UV treatment	−2	−1
No discharge (composting toilet, pump-out system, portaloo)*	−8	−5
Land irrigation of effluent by surface irrigation	−1	−1
Land irrigation of effluent by sub-surface release (e.g. septic)	−2	−2
Buffer zone of 50 m or more in land irrigation area**	−1	−1
Industrial sites		
Secondary treatment	−2	−1
Chlorination	−3	0
Lagoon treatment	−2	−1
Vetiver grass wetland treatment	−2	−2
No local release (hazard is physically removed from site)	−10*	−5*
Land irrigation of effluent by sprinklers	−1	−1
Land irrigation of effluent by sub-surface release	−2	−2
Buffer zone of 50 m or more in land irrigation area**	−1	−1
Agricultural animal sources		
Paddock has a 10 m buffer zone with intact fencing	−1	−1
Grazed area is set back 50 m or more from waterway#	−1	−1
Management practices to remove scats	−1	−1
Management practices where animals are housed in barns	−2	−1
Recreational sites		
Toilets present and functional at recreational site	−1	−1
Site unlikely to have small children recreating in water	−1	−1

*These score modifiers are arbitrary and assume efficient removal of contaminants from the catchment (they do not represent microbial fate and transport processes). These mitigation values may be compromised in the event of overflows or poor maintenance procedures.
**This is included as distance from waterway affects consequence as well as likelihood.
#This is included as distance from waterway affects consequence as well as likelihood.

are described as modifiers to the raw scores from Table 10; the final score is then compared to the consequence ratings (Table 8). Agricultural chemical inputs are treated in a qualitative manner, with consequences rated as 'minor', 'moderate' or 'major' as outlined in Table 9.

Stormwater consequences

Where possible, stormwater which is well characterised with respect to flow and water quality parameters can be examined using a concentration and flow derived load approach. However, it is rare that such data are available for stormwaters, and the relative inputs from sources within a stormwater catchment are usually highly variable. For urban stormwaters, *E. coli* and protozoa scores are assigned along with a consequence rating, as described in Table 12. This differs from the method used for sewage, industrial 'wet' discharge and agricultural sites, because the scores are estimated rather than derived from literature values. The scores are, therefore, only used as a guide for the qualitative consequence rating. For urban stormwaters and industrial 'dry' sites, the chemical hazard consequences (if present) are assigned a qualitative value as described in Table 9. 'Dry' industrial sites can include golf course fuel and chemical storage, services station fuel storage and concourse, council tip and depot fuel and chemical storage, timber mills, mine sites, car parks and WTP chlorine storage. Table 9 can also be used to consider road and bridge locations where fuel spills could occur.

The consequence rating for an urban stormwater site is determined by combining the size of the stormwater catchment with the amount of sewage contamination which can be mobilised by stormwater flows. This requires some knowledge of the type of local sewage infrastructure present and its functionality, which is gathered during the sanitary survey.

For example, a small town with on-site sewage systems and a kerb and gutter system draining to a stormwater drain, which then empties to a waterway, is considered an 'almost certain' source of contaminants from the earlier estimation of likelihood. If survey information suggests the systems and disposal areas are in general functioning properly, then the consequence of the drain would be rated according to stormwater catchment size with the 'well-maintained on-site systems' row in Table 12. The town size would be included as either a large or very large stormwater catchment. However, if there is substantial evidence of functional problems, such as undersized application areas, a history of flooded systems, or

Table 12 | Matrix of consequence for microbial hazards entering waterways from stormwater systems

Hazards	Very small catchment (individual block)	Small catchment (city block or street)	Large catchment (multiple city blocks or streets)	Very large catchment (town or suburb)
No sewer system Failing on-site systems	Moderate *E. coli* 6 Protozoa 4	Major *E. coli* 8 Protozoa 5	Catastrophic *E. coli* 10 Protozoa 6	Catastrophic *E. coli* 12 Protozoa 7
No sewer system Well maintained on-site systems	Minor *E. coli* 4 Protozoa 3	Minor *E. coli* 5 Protozoa 3	Moderate *E. coli* 6 Protozoa 4	Major *E. coli* 8 Protozoa 5
Combined sewer/stormwater infrastructure High density urban	Minor *E. coli* 5 Protozoa 3	Moderate *E. coli* 6 Protozoa 4	Major *E. coli* 8 Protozoa 5	Catastrophic *E. coli* 10 Protozoa 6
Combined sewer/stormwater infrastructure Low density urban	Minor *E. coli* 4 Protozoa 3	Minor *E. coli* 5 Protozoa 3	Moderate *E. coli* 6 Protozoa 4	Major *E. coli* 8 Protozoa 5
Separate sewer/stormwater infrastructure High density urban	Insignificant *E. coli* 3 Protozoa 2	Minor *E. coli* 4 Protozoa 3	Moderate *E. coli* 6 Protozoa 4	Major *E. coli* 8 Protozoa 5
Separate sewer/stormwater infrastructure Low density urban	Insignificant *E. coli* 2 Protozoa 1	Insignificant *E. coli* 3 Protozoa 2	Minor *E. coli* 4 Protozoa 3	Moderate *E. coli* 6 Protozoa 4

visual evidence of flows from properties to gutters, then the drain would be instead rated using the 'failing on-site systems' row, resulting in an overall rating of 'catastrophic'.

Recreation

To evaluate the impact of recreational activities on the quality of raw water supplies at individual locations, each recreational site is treated as a potential contamination point source. This module estimates the potential input of *E. coli* and *Giardia* from each bather to quantify the consequence from the point source.

Two major contamination routes from bathers have been identified – microbial shedding from bathers, and accidental faecal releases (AFRs). For primary contact recreation, the estimated microbial load from AFRs was substantially (more than an order of magnitude) greater than the load from shedding. Allowing for a frequency of one in 1,000 bathers contributing AFRs, a load of 10^6 *E. coli* per bather was calculated (Anderson *et al.* 1998). AFRs were regarded as less likely in secondary contact recreation, with shedding regarded as the more likely route of contamination, and a load of 10^4 *E. coli* per recreator was estimated. For passive recreation, no connection with the waterway exists, however a small proportion of people passively recreating may indulge in either primary or secondary contact recreation or may defecate adjacent to the waterway. We assign a 1% consequence of secondary recreation to passive recreation to reflect this possible outcome. These loads form the basis of the *E. coli* scores described in Table 10. The protozoa score has been scaled three orders of magnitude lower than the *E. coli* score to reflect its lower abundance in human excreta/sewage. The mitigation measures applicable for the recreational site are calculated from Table 11, and compared to Table 8 to derive the overall consequence rating score of 'major', 'moderate', or 'minor'.

The number of individuals at recreational sites is highly variable. In estimating the minimum numbers of people at a designated recreation site, a minimum consequence of impact from 10 individuals is used, to more realistically assess the risk at a site which may have few or no people present at the time of survey.

Calculate risk for individual sites

As per Risk Management Standard ISO 31000 (ISO 2009), risk is calculated as the combination of likelihood and consequence, via the use of a risk matrix, as presented in

Table 13 | Risk matrix for individual sites

Survey risk rating		Consequence: Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain	Medium	High	High	Very high	Very high
	Likely	Medium	Medium	High	High	Very high
	Possible	Low	Medium	Medium	High	High
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Medium	Medium

Table 13. A risk calculation is made for each relevant contaminant at every site surveyed. The individual site risk assessment process provides risk ratings for surveyed sites ranging from low to very high.

Calculating cumulative risk for sub-catchments and catchments

Approach to calculation of cumulative risk

Where catchments are large or complex, they can be described as a network of sub-catchments. The methodology to calculate an integrated cumulative catchment risk uses the likelihood and consequence data gathered from surveyed sites within the sub-catchments. It returns a cumulative score for each of the assessed contaminant types – *E. coli*, protozoan pathogens and chemical contaminants, as determined from the data collected for each of the source hazard modules, STPs, on-site systems, industrial, agricultural, stormwater and recreational sites. A conceptual model of the process is shown in Figure 2.

As the contaminant scores are quantitative they can be used to estimate an overall catchment risk score, allowing for the prioritising of risk management activities across catchments. The calculation of cumulative risks requires the inclusion of all risks from upstream sub-catchments. Some upstream attenuation is assumed from processes such as microbial die-off and sedimentation. The amount of such attenuation is dependent upon the particular conditions of the watercourse. The tool accounts for this in a highly simplified manner whereby the cumulative scores for the sub-catchment (*E. coli*, protozoa and chemical) are reduced by one when they pass through a large waterway or stream reach, and by two when passing through a large

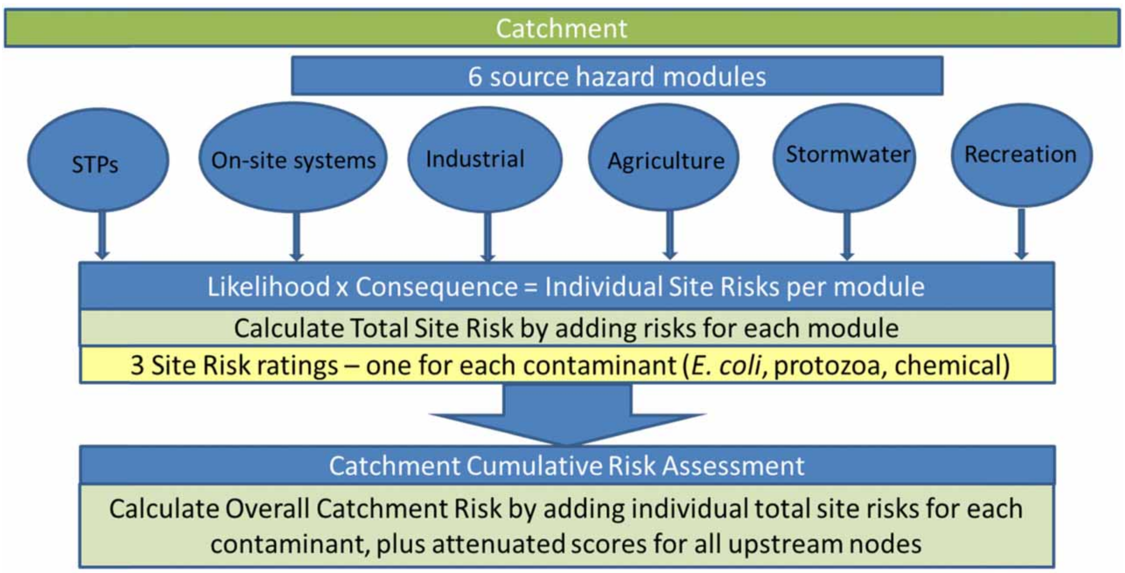

Figure 2 | Conceptual model for the estimation of cumulative catchment risk.

storage. Whilst this method is simplistic, the purpose of the tool is to prioritise hazards and is not intended to replace full-scale stochastic catchment models.

Calculation of cumulative risk

The process of calculating the cumulative risk scores is performed as follows.

The surveyed sites are assigned to sub-catchment areas. The sub-catchments can be thought of as the nodes in a network connected by watercourse flows or pipeline structures.

The surveyed site data for site type, hazard likelihood and hazard consequence (for *E. coli*, protozoa and chemicals) scores are collated.

The consequence scores for *E. coli*, protozoa and chemicals calculated, as described previously, are modified to incorporate the likelihood score to generate the modified risk score (MRS) with negative values of an MRS brought up to zero.

$$\text{Modified risk score} = \text{Consequence score} - (5 - \text{Likelihood score}) \tag{1}$$

The cumulative risk score is calculated, using the MRS, for each sub-catchment, for each of the hazard types (*E. coli*, protozoa, chemical), and for each of the site types (STPs, on-site systems, industrial, agricultural, stormwater, recreational). As the microbial scores are derived from a logarithmic value, the MRSs are not added arithmetically (e.g. $x + y$) but logarithmically (e.g. $\log(10^x + 10^y)$).

An estimate of the survey's completeness is made. Estimation of survey completeness is required for each of the different site types. This can be defined as the proportion of sites of one type which were assessed in the survey, as a percentage. The cumulative consequence for the sub-catchment for one site type can be expressed as:

$$\log\left(\frac{10^C \times (100\%)}{(F\%)}\right) \tag{2}$$

where C is the cumulative consequence estimated from surveyed sites of that site type within one sub-catchment, and F is the estimated survey completeness for that site type. For STPs, all sites in a catchment will have been surveyed. For on-site systems, industrial, agricultural, stormwater, and recreational sites, the total number of catchments sites can be estimated from Census statistics, land use data, council information and local knowledge. Once the survey completeness is estimated, the cumulative score for each sub-catchment from each of the site types is adjusted to account for these estimates.

The cumulative scores from each site/module type for each sub-catchment are combined to give a cumulative score for that sub-catchment.

Where sub-catchments connect to each other, the output from the upstream sub-catchment is an input to the downstream sub-catchment. Each such input is treated as an additional site affecting the downstream sub-catchment, and adding to the downstream cumulative consequence. The hazard likelihood of an upstream sub-catchment is always 'almost certain'; the hazard consequence is the cumulative score of the upstream sub-catchment, subtracting an attenuation factor (0 for minor tributaries, 1 for large waterways, and 2 for a large storage).

The risk at sub-catchment level (for the different module types, and for the combined inputs for the whole sub-catchment) generates an overall cumulative risk rating as described in Table 14.

Outcomes of the cumulative risk analysis

The cumulative risk information is typically presented in a conceptual model/infographic format for each catchment. The outcome for each sub-catchment is represented as a series of pinwheels for each of the three contaminant types (*E. coli*, protozoa, and chemical). The overall cumulative results for the catchment are shown as a set of pinwheels at the top of each diagram.

Table 14 | Risk matrix for cumulative effects at catchment level

Rating	*E. coli* score	Protozoa score	Chemical score
Very high	8 or more	6 or more	5 or more
High	4 to 7	3 to 5	4
Medium	2 to 3	2	3
Low	1 or less	1 or less	2 or less

The mapping of cumulative risk information in this manner presents several advantages when used to complement the mapping of individual sites. The privacy of individual site information is maintained with the grouping of estimates for each site/module types at the sub-catchment level. The relative impact of the different site types is more apparent than when the individual sites are considered. This allows identification of what type of input is having the greatest impact, and in which sub-catchment the sites needing priority catchment management attention are located. Where there are multiple points of vulnerability (drinking water off-takes and recreational sites), the relative risk to those points in different sub-catchments is made readily apparent, as well as what site/module types are assessed as the source of that risk.

The quantitative basis of the cumulative risk assessment allows comparison of the relative risks at points of vulnerability in different catchment areas, and the prioritisation of remedial actions on that basis. In large and complex catchment areas, the cumulative risk approach allows the incorporation of risk information from extremely large numbers of sites, resulting in an estimation of risk to multiple points of vulnerability in a consistent and defensible fashion. The systematic nature of the methodology, and its application across all catchments, enables comparison between catchments across a wide geographical area.

RESULTS

Verification of risk assessment

Once a catchment has been surveyed and the results of the individual and cumulative risk assessments obtained, these results can be verified using two different approaches. The first uses existing water quality data. The second uses novel analytical techniques to provide supplementary information about water quality within the catchment.

Historical water quality data review

Long-term monitoring data are collated and reviewed for in-storage water quality and for the classification of recreational sites, in accordance with NHMRC (2008). The review includes basic statistical analysis of available microbial and chemical data, including pesticide and hydrocarbon data. The review of historical water quality information facilitates an understanding of contaminant loads at sites, and can be used to verify the sub-catchment and whole of catchment risk determinations.

Microbial source tracking study

Novel microbial source tracking (MST) analysis is undertaken on waterway sites and sub-catchments considered high microbial risk. MST parameters can aid in the resolution of human, bird and herbivore faecal sources (NHMRC 2008). The MST methodology involves initial analysis (MST1) of a range of standard analytical parameters including *E. coli* and Enterococci to indicate the potential presence of faecal contamination. Once established as likely to be contaminated with faecal material, further analysis (MST2) involves the detection of genetic markers specific for bacteria which inhabit the gut of particular animal groups. MST1 testing includes *E. coli*., Enterococci, ammonia, turbidity, and pH. MST2 testing includes Bacteriodales (a general faecal contamination marker), Human *Bacteroides* Marker (HBM) and Animal *Bacteroides* Marker (ABM).

When the results of the MST1 testing indicate the likelihood of faecal contamination is rated as either medium or high, then subsequent analysis with the MST2 analysis suite is recommended. This suite of novel testing enables the discrimination of human and animal sources of faecal pollution and can be applied to sub-catchments or specific locations with very high or high risk microbial hazard scores. Very high risk scores related to STPs would be expected to have positive MST signals for HBM, whilst high risk scores related to agriculture sources would be expected to have positive MST signals for ABM. Whilst recreational sites and sub-catchments with on-site systems may test positive for HBM, the strength of this marker is only sufficient to signal very high risk human sources. The complete MST assessment methodology has been described in a previous project funded by the Victorian Smart Water Fund (Ecowise Australia 2010).

The comparison of sanitary survey results with MST results enables water managers to verify sources of contamination at waterway hotspots, to verify sub-catchment and whole of catchment risk determinations, and to trigger further investigation where required. Such information can be used to inform catchment management initiatives or off-take regimes.

Case study

The methodology has been applied to more than a dozen drinking water catchments in south-east Queensland. Catchment A was surveyed in 2011 and 2015, and includes a creek which is subsequently impounded for a drinking water supply. The creek runs through a township with high risk sources including SPS, stormwater and a biosolids pile, and then receives flows from two tributaries which also contain multiple sources of contaminants including dairy, cattle grazing, and an area of failing on-site systems. Water quality monitoring data were available from four locations for the period 2011 to 2015. The spatial relationship between the land uses, sites, sub-catchments and hydrologic flow path are conceptualised in Figure 3.

Table 15 shows a comparison of the cumulative risk ratings for the two surveys. After the first survey, the STP in sub-catchment B was upgraded to discharge to a well-controlled land application area, which removed the possibility of sporadic discharges to the creek during wet weather. This reduced the cumulative risk from 8 to 6 for *E. coli* and from 5 to 2 for protozoan risks from STP infrastructure in sub-catchment B. However, the overall result for sub-catchment B (11:8:3) was still dominated by the agricultural inputs, which were unchanged between 2011 and 2015.

Comparison of risks in sub-catchment D from 2011 to 2015 indicate the importance of capturing representative sites for each of the types of hazardous activities that occur there, noting that these activities are often dynamic. The 2011 survey captured the impacts from on-site systems, however in 2015 an additional eight agricultural sites were surveyed in sub-catchment D and of these three were ranked very high risk for protozoa and either very high or high risk for *E. coli* contamination. The other five sites were also ranked medium risk for microbial contamination. Additional inputs from an SPS and stormwater were also captured. However the increased overall cumulative risk for this sub-catchment from 7:4:2 to 10:7:2 was determined by the agricultural risks.

In sub-catchment C, there was an overall reduction in risk (11:8:3 reduced to 8:5:3) as a result of remedial actions that were implemented at a dairy. The dairy improved on-site effluent handling, and prevention of run-off to the creek from holding yards reducing the cumulative risk score. Figure 4 shows the *E. coli* monitoring results for the four sites in Catchment A for the period 2010 to 2015. Site 2 is the most downstream site in the catchment, and shows some evidence

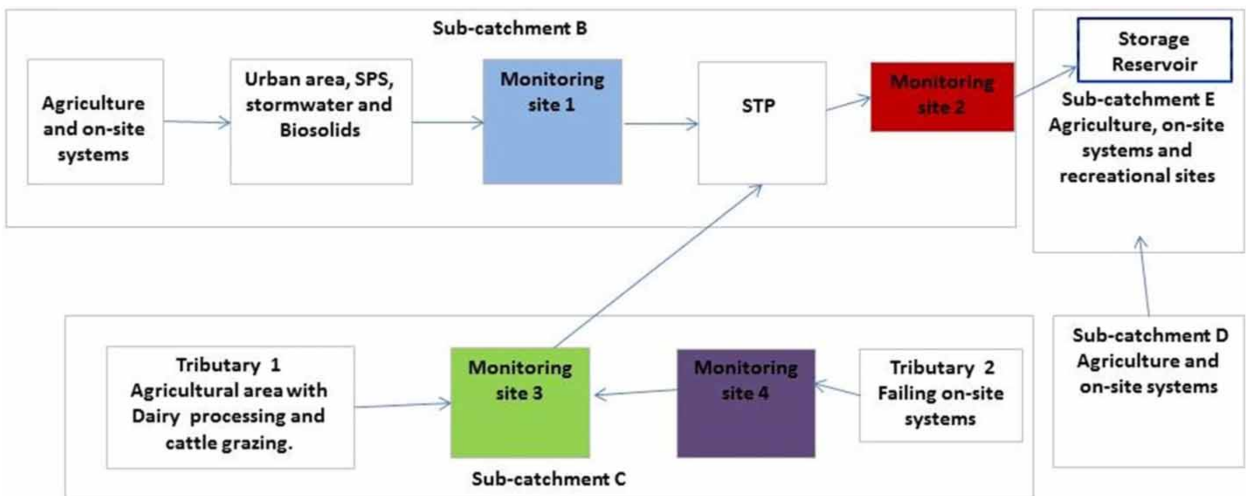

Figure 3 | Conceptual model of Catchment A.

Table 15 | Comparison of risk outputs for Catchment A* surveyed in 2011 and 2015

2011 survey	**Sub-catchment B**			**Sub-catchment C**			**Sub-catchment D**			**Sub-catchment E**		
Module	E	P	C	E	P	C	E	P	C	E	P	C
STP	8	5	0	0	0	0	0	0	0	0	0	0
On-site	4	4	3	4	3	3	7	4	2	3	2	2
Industrial	0	0	0	2	0	0	0	0	0	0	0	0
Agriculture	11	8	3	11	8	1	0	0	0	9	6	1
Stormwater	0	0	0	0	0	0	0	0	0	0	0	0
Recreation	7	4	0	7	7	0	0	0	0	6	3	0
Upstream	11	8	3	–	–	–	0	0	0	11	8	3
Cumulative risk score	11	8	3	11	8	3	7	4	2	11	8	3
Downstream sub-catchment		E			B			E				
Attenuation value		0			0			−1				
Attenuated sub-catchment value	11	8	3	11	8	3	6	3	1			
2015 survey	**Sub-catchment B**			**Sub-catchment C**			**Sub-catchment D**			**Sub-catchment E**		
Module	E	P	C	E	P	C	E	P	C	E	P	C
STP	6	2	1	0	0	0	2	0	0	0	0	0
On-site	4	4	3	8	4	3	7	4	2	3	2	2
Industrial	0	0	0	2	0	0	0	0	0	0	0	0
Agriculture	11	8	3	7	5	1	10	7	2	9	6	1
Stormwater	4	2	2	4	2	1	1	0	0	5	3	1
Recreation	7	4	0	0	0	0	0	0	0	7	4	0
Upstream	8	5	3	–	–	–	0	0	0	11	8	3
Cumulative risk score	11	8	3	8	5	3	10	7	2	11	8	3
Downstream sub-catchment		E			B			E				
Attenuation value		0			0			−1				
Attenuated sub-catchment value	11	8	3	8	5	3	9	6	1			

*Overall Catchment A risk = Outlet of sub-catchment E, which includes direct inputs from areas surrounding the reservoir and inputs from upstream catchments B, C and D.

of decreased *E. coli* concentrations following the upgrade to the STP. However, it is difficult to distinguish this from the noise in the data with runoff from rainfall events in December/January 2015 still causing spikes in *E. coli* concentrations at all four sites, probably originating from the on-site systems upstream of Site 4 in sub-catchment C.

Figure 4 shows that water quality between Sites 1 and 2 (upstream and downstream of the STP) was not greatly different after the upgrade to the STP. Additionally, *E. coli* concentrations in the small tributary creeks were greater than in the receiving creek, frequently by an order of magnitude. Where downstream (Site 2) concentrations were elevated, these could be attributed to flows from the small creeks (Sites 3 and 4) rather than from upstream urban inputs (Site 1) or from the STP. It was concluded that the improvements to water quality related to the STP upgrade are largely masked by the continued input of other sources upstream of Site 2. This conclusion was confirmed by the risk assessment from the second survey. The two improved sites that were initially assessed as very high risk were subsequently assessed as of low risk in 2015 due to the improvements made. Other than sub-catchment C, which showed reduced risk as a result of the dairy upgrade, the assessed cumulative risks of the sub-catchments were not

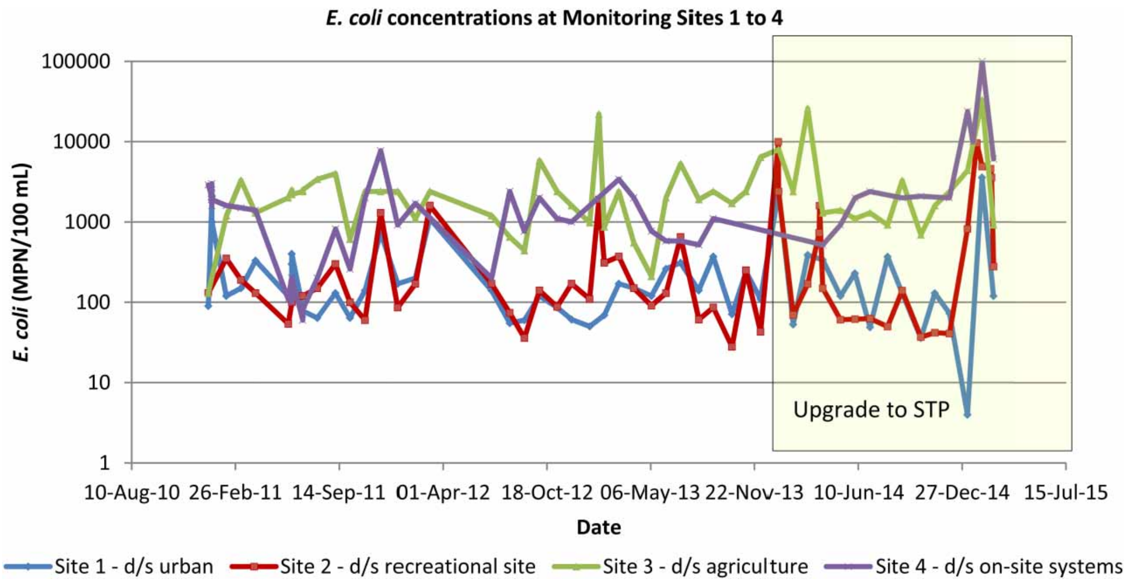

Figure 4 | Water quality results for Catchment A.

altered despite these improvements, due to the presence of the other upstream sites still assessed as high or very high risk.

DISCUSSION

The sanitary survey methodology and the use of the associated electronic capture tool allows for the systematic identification, data capture and quantification of risks in water catchments. The tool goes beyond the existing guidelines for catchment water quality risk evaluation to provide a set method for the quantifying, ranking and comparison of multiple index hazards across the most relevant site types for assessment. A major point of difference between the methodology and other survey guidance is the ability of the information to be directly matched to the risk assessment process typically applied to drinking water treatment systems. The WHO Guidelines for Drinking Water Quality (WHO 2011) promote the health based targets approach to be applied to the whole of a drinking water system, as does the Australian Drinking Water Guideline (NHMRC & NRMMC 2011). This methodology allows for a logarithmic based risk grading for the raw supply, which can be validated by the raw water quality monitoring, and can ultimately be matched with the risk assessment and health based targets for drinking water treatment and supports a catchment to tap assessment.

The WHO (Barrenberg 2014) developed a tool for the assessment of small water supplies at the point of treatment, and considered whether to develop a hazard identification tool versus a risk assessment tool. The survey methodology presented here provides a severity level for mitigated risk and therefore does both. Previous methods have focused on hazard identification through sanitary inspection, with no bridge to the risk assessment process.

Sanitary inspection is essential as a lead or predictive indicator for catchment risk and to support management intervention. Water quality monitoring at the point of treatment is a lag or surveillance indicator, which can be used for the verification of sanitary inspection and to inform on the location of risk hotspots in need of sanitary assessment. Water utilities and those responsible for beach and lake recreation sites are now embracing the virtue of using both systems of monitoring, and this methodology supports the use of sanitary inspection and monitoring in conjunction.

Routine *E. coli* monitoring data from four points in the area of interest were available, on examination it was not clear if any improvement to water quality was apparent following the remedial works. This highlighted several conclusions regarding the application of the survey approach. Firstly, a site with low probability but high impact of effect on water quality can be assessed as of very high risk. Remediation works to such a site may not result in any effect observed by ongoing water quality monitoring, due to the low frequency of occurrence, but may reduce the assessed risk to the catchment. Secondly, where several sites are clustered together, it can be difficult to isolate the effect of any single site or remediation to one site. For improvements to water quality to become apparent, the remediation of most or all of the high risk sites along a waterway reach may be necessary. Thirdly, the methodology includes an estimation of the proportion of sites of different types which have been surveyed. Hence, when a subsequent survey reveals high-risk sites not originally included, the apparent risk can be increased despite actual improvements in the catchment. In this case, this was evident in sub-catchment D.

Techniques such as MST can be of use to identify where contamination is originating from, and provide some verification of assessed risks. The use of MST to verify the surveyed sources of contamination aligns with the US EPA practice of applying these in both recreational sanitary surveys and in developing Total Maximum Daily Loads for waterway protection (USEPA 2013). The methodology also aligns with the WHO Guidelines for Safe Recreational Water Environments (WHO 2003), which outlines a combined sanitary inspection and microbial measurement for classifying recreational waters. Whilst both MST and water quality monitoring are used to verify and inform a sanitary survey in a feedback loop, the cost and effort of undertaking frequent comprehensive monitoring can be a burden. This tool can help to refine and reduce the monitoring effort required for a catchment and assist the interpretation of water quality monitoring, which is often not well interpreted or linked to catchment management actions.

CONCLUSIONS

The described methodology systematically gathers sanitary survey information relevant to water quality in a catchment, and uses the information to estimate water quality risks for identified hazard sources. The risk information is combined to estimate cumulative risk and to attribute the impact of source hazards at sub-catchment and catchment levels. The outputs are relatively simple to interpret, and can be applied in different catchments for comparative purposes.

The risk estimates produced by the methodology are able to be verified by approaches such as the examination of historical water quality monitoring data, and the use of MST methods. Such approaches are used to support conclusions about dominant contamination sources, and the amount of contamination occurring in a sub-catchment area.

The systematic collection and evaluation of catchment information greatly enhances the uniformity and reliability of data collection, as well as making such information easily available for further analysis, risk assessment and decision making.

This methodology has been directed towards the protection of drinking water supplies and the identification of potential hazards to recreational waters. However, it can also be applied to the identification of pollution hotspots in urban and peri-urban areas, to assist in the prioritisation of infrastructure projects such as sewer back-log programs and improvements to the management and design of urban stormwater infrastructure.

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