The pollution source assessment tool for Sydney's drinking water catchments

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ABSTRACT

WaterNSW funds a range of interventions to minimise pollution within the drinking water catchments of Sydney. To assist with the process of targeting this expenditure, WaterNSW has developed a spatial analysis tool, known as the Pollution Source Assessment Tool (PSAT), which uses a hybrid of multi-criteria analysis and load-based methods to highlight high pollution potential sites and critical source areas for pathogens, nutrients and suspended sediment. The design of the PSAT enables results to be summarised by any set of spatial units and with any combination of pollution sources. The most recent PSAT outputs have been used at multiple scales; to guide identification of priorities across the whole of the drinking water catchments of Sydney and also to target programmes on individual properties, sites and urban areas.

Key words | catchment, multi-criteria analysis, pollution, prioritisation

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INTRODUCTION

Management of a large drinking water supply catchment requires understanding of the pollution characteristics of each of the land uses it contains. Given finite resources to address sources of water pollution, decision-makers must decide where and how to intervene to maintain or improve water quality, and the allocation of resources to each intervention. Usually there is a clear need to justify the decisions made and to be able to repeat the assessment process to test decisions or to examine change over time (Caruso 2001; Seymour et al. 2008).

This task becomes complex in catchments with a wide diversity of pollution sources; point and diffuse, large and small, urban and agricultural, which can vary significantly in when and how they deliver pollutants to stream, and how their potential to pollute could be addressed (Ongley & Booty 1999). Catchment management agencies employ a range of methods to prioritise point sources and critical source areas for catchment interventions. The choice of method requires consideration of the precise aims of the prioritisation, the spatial scale of the work and the data available (Bloodworth et al. 2015).

One common approach is export coefficient modelling (ECM), which combines estimates of pollutant export rates for diffuse sources with averaged or time series rainfall data to produce estimates of potential pollution load (e.g., McNamara & Cornish 2005). These models produce load estimates for functional units such as land use classes or catchments and can be used as an input to a broader risk assessment (Waterhouse et al. 2012; Overheu et al. 2014) or as one component of a pollutant budget model, which accounts for point and diffuse sources and considers pollutant loss in transport to model the pollutant delivery in a whole system (Adinarayana et al. 1995; Argent et al. 2005; Bryan et al. 2009). Pollutant budget models have previously been applied to the drinking water catchments of Sydney for both sediment (Rustomji et al. 2008) and pathogens (Ferguson et al. 2004).

These methods enable prioritisation of whole catchments and/or classes of land use; however, they are of little assistance for identifying critical source areas of pollutants. To address this need, several studies have used spatial analysis to model patterns in pollution generation and create

spatially distributed estimates of pollutant export rate (e.g., Endreny & Wood 2003). It is, however, a difficult task to create meaningful spatially distributed export coefficients, considering the diversity in land use, topography, soils, land management practices present in each grid cell. Spatially distributed export coefficients are more data-hungry and difficult to validate than lumped coefficients and this may result in poorer modelling performance overall (Álvarez-Romero et al. 2014).

A key strength of load modelling is that its outputs use a metric, pollutant load per unit time, which is comparable between pollution sources and easy for decision-makers to understand. Where data requirements are prohibitive, it is necessary to base decision making on a less precise output; index values representing a 'priority objective' such as pollution hazard or site suitability, which are typically informed using a combination of available data and expert judgement (Ongley & Booty 1999; Zhang & Huang 2011).

This approach is known as multi-criteria analysis (MCA) (Greiner et al. 2005; Chon et al. 2012). When the process is carried out for spatially located grid cells or sites, rather than a table of alternatives, the process is known as GIS-MCA (Castellanos Abella & Van Westen 2007; Oliver et al. 2010; Zhang & Huang 2011). The reduced data requirements of GIS-MCA over load modelling means that it is a more feasible method for discriminating between pollution sources at a fine spatial scale. Prioritisation can therefore be carried out within different classes of land use in response to fine scale variation in landscape and land management characteristics.

One limitation of MCA is that the meaning of the index is often vaguely defined (Malczewski 2006). Load modelling approaches can incorporate any source if the necessary export rates are available. However, with MCA it may not be possible to apply a consistent definition of pollution hazard, or even the same set of assessment criteria, to different classes of land use. This is particularly true when comparing point sources such as sewage treatment plants with diffuse sources such as agricultural areas.

This paper describes the Pollution Source Assessment Tool (PSAT), developed by WaterNSW to prioritise the broad range of potential sources of pollution in the drinking water catchments of Sydney, Australia. The PSAT contributes to the effective management of these catchments by WaterNSW; a role defined in the Water NSW Act 2014. The PSAT addresses the shortcomings of both ECM modelling and GIS-MCA by using a hybrid of the two methods. This approach, in which the outputs of multiple GIS-MCA's are scaled using annual average pollutant export rates, produces a flexible set of outputs which can be summarised at any spatial scale and in which potential export rates (scaled hazard indices) from any combination of pollution sources can be combined and prioritised against other options.

The aim in creating the PSAT was to provide a framework for characterising the pollution hazard of all likely sources of pathogens, nutrients and suspended solids in the drinking water catchments of Sydney, and the pollution risk of various combinations of sources to its streams and storages. This framework has several purposes:

1. To provide a means for gathering, summarising and storing expert knowledge, scientific data about the pollution sources, particularly in relation to their risk factors, both natural and human-derived.
2. To provide a consistent, understandable methodology and spatial system for rating the priority of pollution sources, both within different classes of pollution sources and between them, providing a clear justification for allocation of expenditure among sources and geographic areas within the catchments.
3. To provide a flexible system for summarising and interpreting outputs, enabling them to be used for decision-making at any spatial scale (field, property, town, drainage unit, major catchment).

METHODS

Scope

The 2016 pollution source assessment focused on pollutants which are recognised by WaterNSW as being of greatest significance in the management of raw water for the drinking water supply of Sydney (WaterNSW 2015; NHMRC & NRMMC 2016). These are:

- pathogens that are known in the study area and have long persistence times, namely, *Cryptosporidium* and *Giardia* spp.;

- phosphorus and nitrogen, which are contributors to cyanobacteria blooms;
- suspended sediment, which can cause difficulties in treatment processes.

The assessment encompassed all likely sources of the above pollutants in the drinking water catchments of Sydney with the exception of river bank erosion, which has been previously assessed as having low significance in the study area (Rustomji 2006).

The pollution sources were categorised into the following 13 groups:

1. Grazing
2. Gully erosion
3. Horticulture and cropping
4. Forests
5. Industry
6. Intensive animal production
7. Landfills
8. Mines and quarries
9. On-site wastewater systems
10. Roads
11. Sewerage treatment plants
12. Sewers and pumping stations
13. Urban stormwater

These are known as 'pollution source modules'. The assessment for each pollution source module was carried out using the same broad method but a unique set of criteria, inputs and weightings for each module. This approach was adopted to ensure that the most appropriate criteria were used to characterise the pollution potential from each source.

Study area

The drinking water catchments of Sydney (Figure 1), hereafter referred to as 'the catchments', cover almost 16,000 square kilometres. They extend from the headwaters of Coxs River north of Lithgow to the Shoalhaven River south of Braidwood. They drain into 11 major dams, storing raw water which is released via a network of rivers, pipes and canals to water filtration plants prior to distribution to drinking water customers.

The catchments contain a population of around 120,000 people across 15 local government areas, and a diversity of land uses including native forest (50.2%), agricultural land (37.3%), forestry (5.7%), intensive uses such as urban areas, industry, intensive animal production, mining and waste management (4.9%) and water bodies and streams (1.9%) (GHD 2013, p. 16). The catchments were divided into 27 sub-catchment areas, which were further divided into 210 smaller areas based on stream order and location of water monitoring sites. These are referred to as 'drainage units', and were adopted as the primary unit for high level decision-making about catchment interventions. All catchment boundaries used in the PSAT were generated from a 25 m digital elevation model and analysed using hydrological modelling tools in ArcGIS.

Although the catchments represent only 2% of the land area in NSW, they supply drinking water to approximately 4.5 million people in Sydney, the Illawarra, the Blue Mountains, the Southern Highlands and Shoalhaven. This represents around 60% of the population of NSW.

System design

The spatial datasets used and produced by the PSAT were stored in geodatabases and analysed using ArcGIS and the Spatial Analyst extension. Non-spatial data were stored in MS-Excel spreadsheets and managed in the WaterNSW document management system. The analysis was carried out using custom-built ArcGIS ModelBuilder models and python scripts.

Each combination of module and pollutant was subject to a separate MCA using the same broad methodology but a different set of inputs and weightings. The priority objective for the PSAT assessment was 'pollution hazard', defined as the potential long-term contribution of pollutants to the stream network from each source.

The MCA process (Malczewski 2006) can be generically described using the following steps:

1. A list of alternatives is established, such as sites, spatial regions or decisions.
2. A number of criteria are selected which are judged, based on expert opinion or experimental means, to have influence over the priority objective.
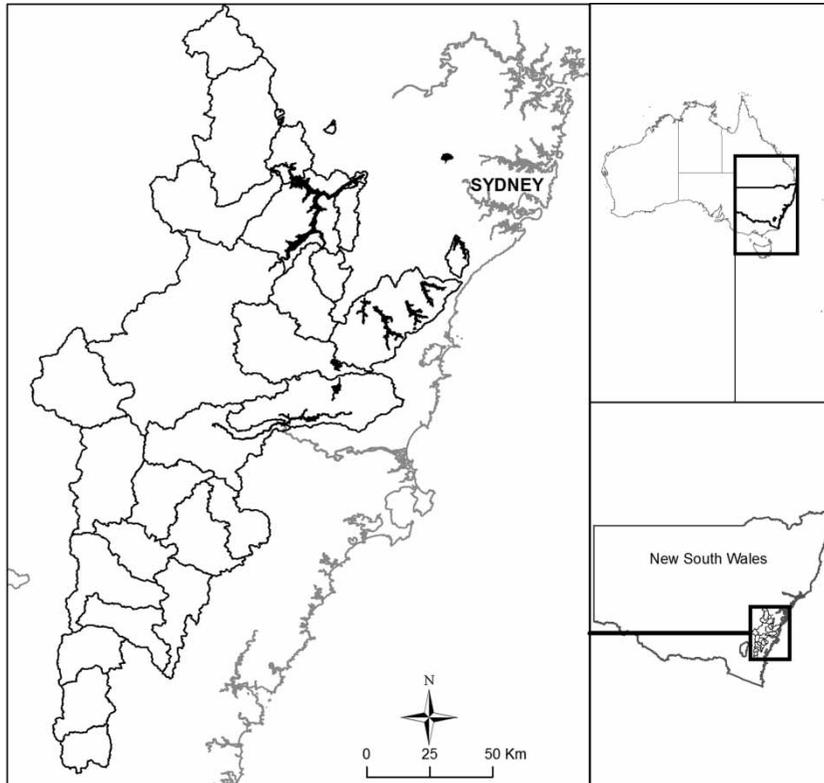
Figure 1 │ The drinking water catchments of Sydney.

3. The criteria are informed by available data and converted to index values for each alternative.

4. The criteria indices are combined using combination rules to create a single index value for each alternative, which allows them to be compared and prioritised.

The PSAT analysis used the weighted sum combination rule. This has the limitation that it does not accommodate interaction or hierarchy of importance between criteria (Carlon *et al.* 2004); however, this was weighed up against the fact that it is the simplest combination method for expert teams and decision-makers to understand. The hazard index for each combination of pollution source module and pollutant was calculated using Equation (1) below.

For *n* decision criteria and *m* spatial sites or grid cells:

$$R_j = \frac{W_1 I_{j1} + W_2 I_{j2} + \ldots + W_n I_{jn}}{\sum_n W_c} \tag{1}$$

where R_j = combined hazard index for spatial unit j (j = 1, 2, 3, …, m); W_c = weighting for criterion c (c = 1, 2, 3, …, n); and I_{jc} = hazard index value for spatial unit j and criterion c.

Implementation

Each individual pollution source module MCA was carried out using the following steps:

1. A team of subject-matter experts was formed from within the organisation. This team, known as the 'module team', had the task of reviewing the analysis design, advising on possible data sources and reviewing weightings and outputs. Use of an internal team can introduce bias; however, this potential was minimised by choosing people with a diversity of expertise and by using a consensus approach to decision-making.

2. The module team developed a conceptual model describing the mechanisms of input of pollutants from the sources, pathways of transport to the stream network and any relevant controls or mitigating factors. See Figure 2 for an example.

3. ArcGIS software was used to identify and define the location of all sources addressed by the module using land use mapping, aerial photography and field
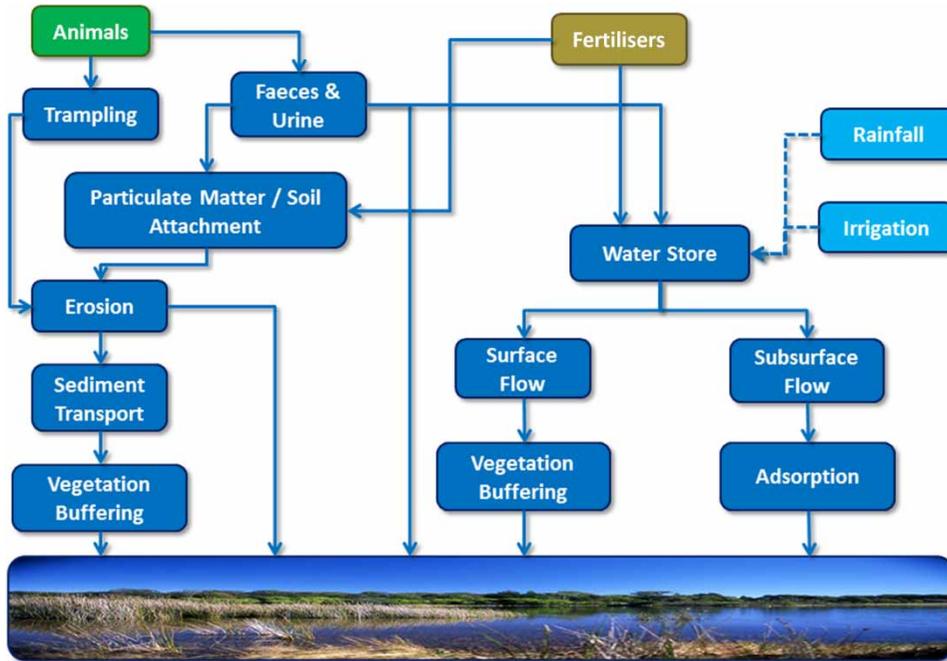
Figure 2 │ Conceptual diagram for the Grazing module.

observations. The data model used depended on the nature of the pollution sources being analysed: point sources were represented by a set of spatial points, while diffuse sources were represented by a set of spatial polygons defining regions of similar management practices, which were subsequently analysed in the form of 25 m grid cells.

4. One input dataset was prepared to represent each criterion in the conceptual model, covering the full spatial extent of the module locations. These took a variety of forms, including the following:

   • topographic modelling outputs;
   • groundcover indices derived from satellite imagery;
   • soil mapping;
   • rainfall interpolation outputs;
   • site specific risk ratings of management practices such as waste disposal or treatment methods;
   • estimates of stock density and associated faecal loadings.

   Detailed information on individual inputs for each module can be found in WaterNSW (2017).

5. Inputs were transformed or categorised into a risk index ranging between 0 (nil risk) and 100 (highest risk). A 0–100 scale was used because it enabled inputs

in numerical form (e.g., rainfall, slope, stock faecal loads) to be transformed to a common integer scale while maintaining high attribute precision. Where categorical inputs were necessary they were introduced as values of 0 (nil risk), 33 (low risk), 66 (moderate risk) and 100 (high risk).

6. The module team reviewed inputs and advised on any changes necessary to analysis or data capture methods. They used a consensus approach to determine a set of weightings to combine inputs. Weightings were different for each pollutant.

7. The pollution potential was then analysed using the relevant data model; point sources were analysed using table calculations, and diffuse sources were analysed using raster calculations. The rating and weighting method was identical regardless of data model. The overall conceptual module design was reviewed by the module team and their advice incorporated into the module and the system re-run if necessary.

   Outputs for point source modules (sewage treatment plants, industry, mines, landfills, onsite sewage systems) are in the form of point datasets with attribute tables

containing summed hazard index values ranging between 0 and 100. There was one field of output values for each pollutant. The outputs of diffuse modules (remaining eight modules) are in the form of raster datasets ranging between 0 and 100, one dataset for each pollutant.

Transformation and scaling

Raw hazard index values are an indication of the potential of individual land units (sites or grid cells) to contribute pollutants to the stream network. They provide a method for prioritising the land units within each pollution source module but are not useful for prioritisation between modules because the inputs and weightings, and therefore the meaning of the index values themselves, are different for each module.

A scaling process was subsequently carried out to convert the hazard indices to a metric that is comparable between modules. The long-term contribution of pollutants to stream by pollution sources is often quantified in the form of annual average export rates, expressed in oocysts/ha/yr or kg/ha/yr, generated from field-based pollutant runoff studies. Predictions of these rates for each land unit, referred to as 'potential export rates', were adopted as the metric for PSAT scaling for the following reasons:

- they quantify pollutant runoff over the sum of wet and dry conditions in a given time frame;
- they reflect the combined effect of land use, management practices, landscape, soils and climate on pollutant generation and runoff;

- they were found to be quantified and published in scientific literature for a wide range of land uses, including point and diffuse sources;
- they have the potential to be used in future distributed load modelling/pollutant budgeting studies.

Figure 3 illustrates the conceptual location of hazard index values for different modules on the scale of potential export rates. The maximum (100) and minimum (0) hazard index values translate to maximum and minimum potential export rates. The range of potential export rates is different for each module.

The scaling of PSAT hazard index values to potential export rates for each module distributes the land units between the maximum and minimum potential export rates, which were estimated by finding the maximum and minimum export values available for relevant land uses in scientific literature.

The relationship between hazard index values and export rates is not necessarily linear. While the frequency distribution of hazard index values is generally normal, the distribution of export rates are often left skewed. For example, sediment export from most roads is relatively low, while a small number of roads in the study area (forestry tracks on steep land with erodible soils) can have very high export rates (Sheridan & Noske 2005). For modules where available data indicated that this was the case, raw results were transformed using a power function. This process is illustrated in Figure 4.

For each module, the transformed index values were then scaled linearly between the minimum and maximum export rates as defined in Equation (2) below.
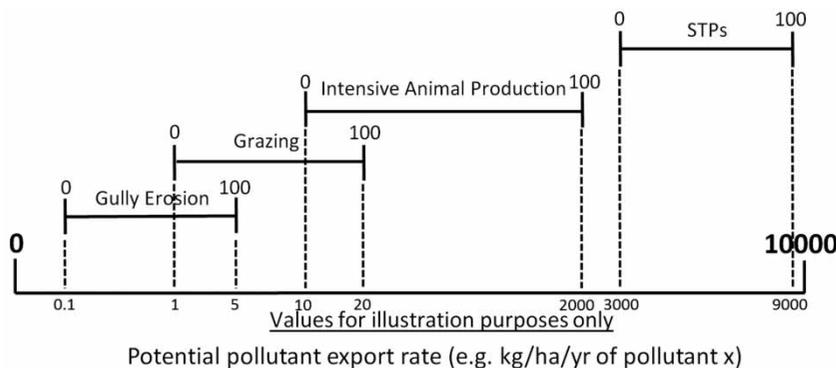

Figure 3 │ Conceptual diagram of relationship between hazard indices for multiple modules and potential export rates.
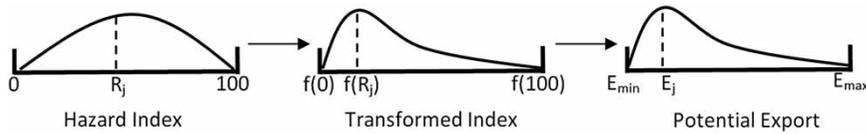
Figure 4 | Illustration of scaling process for a single module.

For m spatial sites or grid cells:

$$E_j = \frac{f(R_j)}{f(100)} \times (E_{max} - E_{min}) + E_{min} \qquad (2)$$

where R_j = raw (0–100) hazard index for land unit j (j = 1, 2, 3, … , m); f(x) = transformation function (power function); E_j = potential export rate for land unit j (j = 1, 2, 3, … , m); E_{max} = maximum potential export rate per land unit in study area; and E_{min} = minimum potential export rate per land unit in study area.

Potential maximum and minimum pollutant export rates (E_{max} and E_{min}) were estimated for each combination of module and pollutant, using published field-based pollutant runoff studies. A web and reference search was carried out for studies producing or summarising annual pollutant export estimates for relevant land uses. In some cases there were insufficient data available for studies within the drinking water catchments, and in those cases studies were used from environments similar to the study area.

Export values were compiled in separate spreadsheets for each module and reviewed. Results were omitted if they were considered to be from sites unrepresentative of the pollution sources in the catchments (for example those from feedlots, which do not occur in the study area). From this list, the minimum of values was adopted as S_{minj} and the 90th percentile value as S_{maxj}. Use of the 90th percentile value omitted extreme values (for example, those from extreme rainfall years or unusual land use practices) which would otherwise skew scaled values.

There was substantial variation in the relevant data available for scaling calculations. Roughly half of the module/pollutant combinations had five or more relevant published rates available, while the remainder had four or less. Rates were estimated based on expert opinion for the Onsite Sewage and Mines and Quarries modules, as no information was available in the form required. Scaling of these modules therefore carries greater uncertainty and is a high priority for future work.

Summation by units

All point source modules were converted to raster, using the same grid cell size (25 m) as diffuse sources. Grid cells containing two or more points were assigned the sum of values. This process produced a full set of 25 m rasters with scaled potential export rates, one raster for each combination of pollutant and module.

The potential export rates in scaled outputs were summed by various units including drainage units, properties, urban centres, local government areas and 1 ha grid cells. As the greatest improvement in water quality through catchment interventions can usually be made by addressing the highest risk sites and grid cells, a set of outputs was also made using only the values from the highest risk quarter of grid cells in each module.

The main scaled output used for prioritisation of modules was the sum of highest risk quarter grid cells by drainage units. These counts were used to categorise drainage units into low, moderate, high and very high risk for each module and pollutant.

RESULTS AND DISCUSSION

The PSAT was run for 13 modules and scaled outputs generated. Table 1 summarises the scaled results, combined across all modules, aggregated by drainage unit, and categorised into high, medium and low pollution potential. The results were generally similar to the outputs from the previous run of the PSAT in 2011 (Sydney Catchment Authority 2011), which used more simple scaling methods. There was, however, reduced assessed risk from sewer infrastructure in comparison with previous years. This can partly be attributed to a history of expenditure by WaterNSW (formerly Sydney Catchment Authority) to improve sewage treatment plants.

Table 1 | Count of high and very high risk drainage units in PSAT results

	Pathogens		Phosphorus		Nitrogen		Suspended solids	
	Very high	High	Very high	High	Very high	High	Very high	High
Grazing	4	12	11	19	4	11	4	37
Gully erosion	0	0	0	0	0	0	8	28
Intensive animal production	1	3	0	8	5	3	0	0
Forests	0	0	0	0	0	23	0	6
Urban stormwater	0	0	0	1	3	3	0	2
Landfills	0	0	0	2	2	1	0	0
Industry	0	0	1	2	1	0	0	0
Horticulture and cropping	0	0	0	0	0	3	0	4
Sewage treatment plants	1	0	0	1	0	2	0	0
Roads	0	0	0	0	0	4	0	1
Sewers and pump stations	0	1	0	0	0	1	0	0
Mines and quarries	0	0	0	0	0	0	0	0
Onsite wastewater management	0	0	0	0	0	0	0	0

The results indicate the following overall priorities:

1. Grazing was assessed as having the potential to contribute the greatest pollutant loads in the catchments. It is a widespread activity and carries significant areas of high pollution potential for pathogens in cattle grazing areas which also have high stock density, slope and rainfall combined with sub-optimal management practices. There is also an increased assessed risk for suspended solids and associated nutrient loads from grazed areas to the west of the catchments which periodically have poor groundcover and are susceptible to drought and over-stocking.

2. Gully erosion remains a significant potential source of suspended sediment; however, the relatively nutrient poor soils in erosion-prone areas mean that it did not rate as a significant risk for nutrients.

3. Intensive animal production sites, and dairies in particular, have high pollution potential due to the concentration of calves and lactating cattle, which excrete substantial quantities of human infective pathogens. These properties experience high rainfall and while improvements in effluent management have reduced the assessed risk of many sites over the past decade, there are still improvements to be made, particularly in the maintenance of effluent structures which can act as sources of pollutants if they fail.

4. Forests with a high risk rating occur in areas with high slope, high soil erodibility and high fire susceptibility; however, these results reflect an inherent (rather than human induced) risk scattered across large areas. While the potential for wildfire to occur in these areas is normally low, erosion can be significant when wildfire is followed by heavy rainfall. The combination of steep, dissected terrain and shallow nutrient-poor soils is not conducive to the development of a stable ground cover or shrub layer. This can result in sheet and rill erosion during high rainfall.

5. Urban stormwater rated as a significant risk in densely developed areas which contain a high proportion of impervious surfaces. These generate high runoff and entrainment of pollutants where storm activity is frequent, particularly where stormwater treatment is poor or absent entirely.

6. Individual industry and landfill sites around the urban fringe pose a high potential risk, particularly where they occur near streams, in higher rainfall areas and are unregulated or poorly managed.

The strength of the PSAT lies in the fact the outputs can be summarised at any scale and in its capacity to weigh up

the pollution potential of all sources – point and diffuse. In parallel with the development of geographic information systems universally, the PSAT has developed from a closed system analysed by one or two experts and then disseminated in the form of paper maps, to a flexible tool whose outputs and components can be explored in a variety of ways by decision-makers. This has been made possible by its hybrid MCA/load-based design and by the extensive use of web mapping applications to enable display and exploration of outputs.

In planning of catchment programs for 2016–2020, WaterNSW has used new PSAT outputs in each of the following ways:

- Raw outputs to highlight highest risk sites and regions within each single module (e.g., identifying the 100 highest risk onsite sewage systems for pathogens, mapping the highest risk horticulture areas for phosphorus).
- Scaled outputs by hectare (summed across all modules) to identify high risk hotspots across all modules for nitrogen and phosphorus.
- Scaled grazing and gully erosion outputs summed by property to target agricultural properties for riparian fencing and rehabilitation.
- Scaled outputs for all modules summed by drainage unit to guide allocation of funding across the various programmes (grazing, sewage, stormwater, etc.).

The PSAT has existed in various forms for approximately 12 years; however, the analysis presented here is the first in which scaling of results has been applied to sites and grid cells rather than catchment areas. This method is currently limited to some degree by the quality of potential maximum and minimum annual export rates used to scale the hazard indices for each module and the simplified relationship between hazard index and potential export rate. For the first time, however, estimates of potential export rate outputted by the PSAT can be combined across all modules and summarised by the catchments of water monitoring sites. This provides the basis for future use of PSAT outputs in pollutant budgeting models and validation against historical water quality data, which may lead to subsequent improvement in components of PSAT scaling and hazard assessment. It also enables examination of in-stream processes such as pollutant deposition and bed load transport, which are not accounted for by the current process. This work will be the subject of a future publication.

The individual risk factors that form the PSAT assessment can easily be modified over time as our understanding of catchment processes improves and as land uses and available catchment interventions change over time. They could also be applied to the addition of pollutants such as metals, hydrocarbons or pesticides if these emerge as issues of concern in water monitoring. The PSAT therefore enables adaptive management of the drinking water catchments of Sydney. A key strength of the PSAT, and of GIS-MCA in general, is that the processes and systems used for assessing the priority of pollution sources can also be used for evaluating the effectiveness of pollution reduction programmes, by exploring alternative scenarios of land use, climate or management practices. This, also, is the subject of ongoing work.

CONCLUSIONS

The PSAT outputs for 2016 provide a comprehensive risk assessment and prioritisation of potential sources of pollution in the drinking water catchments of Sydney. The PSAT highlights the continued potential for pathogens, nutrients and sediment from grazing and intensive animal enterprises in the drinking water catchments of Sydney. It indicates a continued need to address high risk grazing practices, a reduced emphasis on sewage infrastructure in comparison with previous PSAT outputs, and also highlights the risk of specific urban areas and point sources.

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