A New Ecological Footprint Calculation for the Australian Water Industry: Regionalisation and Inclusion of Downstream Impacts

By

Gregory Peters[*], Fabian Sack[**], Manfred Lenzen[***],

Sven Lundie[*] and Blanca Gallego[***]

Abstract

A new calculation of the Ecological Footprint (EF) of a water provider addresses limitations in the previous methodology by regionalising a previously national input-output model, and determining the area of disturbance caused by environmental toxicants not considered in the traditional EF model. In a first step, the regional input-output model determines indirect effects of water services activities in the form of point sources of pollutants. Accuracy is improved by hybridisation using "process data" to account for the direct environmental burden of the water service. The accuracy of the input-output model is improved by reconciling data sources; calibrating concordance tables and employing optimisation techniques to deal with conflicting data sources. The second step involves a nested fate model, which follows the fate of the point source emissions at several spatial scales. The final output provides an indication of the direct and indirect burden connected with the water business, throughout its entire upstream supply chains. This proposed EF methodology improves on previous EF methodologies by avoiding exclusive reliance on national average data, and by including toxicants in a disturbance-based calculation analogous to the established inclusion of greenhouse gases in EF, making it more comprehensive. It is hoped that the additional detail and comprehensiveness will make the new method a more effective environmental reporting and communications tool for the Australian water industry. This generic approach to environmental reporting may potentially be applied to other economic activities.

1 Introduction

The ecological footprint (EF) was conceived as a simple and elegant method for comparing the sustainability of resource use among different populations. Consumption by a population is converted into a single index: the land area that would be needed to sustain that population indefinitely. This area is then compared to the actual area of productive land that the given population inhabits, and the degree of unsustainability is expressed as the difference between available and required land. Unsustainable populations are thus simply populations with a higher EF than available land. EFs calculated

according to this original method became important educational tools in highlighting the unsustainability of global consumption. EFs have also been used for policy development and planning, both in government and industry.

1.1 Use of the EF in the Australian Water Industry

As currently performed, EF allows combined assessment of direct land disturbance and greenhouse gas emissions, incorporating all the contributions to these made by a water corporation's supply chain. Following an initial pilot of the EF in the UK (Chambers & Lewis, 2001) an improved methodology, using the widely accepted economic analysis technique of input-output analysis, has been trialled in the Australian water industry (Lenzen et al., 2003). To date, several Australian Water authorities have used the EF to communicate the combined impact of materials and energy consumed by urban water cycle management activities and each customer's contribution to this impact. The methodology is considered to be mathematically robust, allows some limited benchmarking of performance, and has outputs that are easily communicated to a broad public audience (eg.: newspaper readers-O'Dwyer, 2006). Financial data provides the information required to calculate EF. Since financial systems are generally computerised and audited, data collection for EF use is practical and relatively accurate.

1.2 Methodological Constraints

Since the formulation of the EF, a number of researchers have critiqued the methodology originally proposed (Levett, 1998; Opschoor, 2000; van den Bergh & Verbruggen, 1999; van Kooten & Bulte, 2000). Their comments largely refer to the oversimplification of the complex task of measuring the sustainability of consumption patterns, leading to comparisons among populations becoming meaningless, or the result for a single population being significantly underestimated. In addition, the geographically aggregated form of the final EF makes it difficult to formulate appropriate policy responses to the factors driving unsustainable consumption.

An additional constraint on the use of the EF methodology by the water industry is its inability to include downstream aquatic impacts in the calculation (Lenzen et al., 2003a; Sack et al., 2003). To be accurately applied to industry sectors such as the water industry, where the ecological impact of discharges may be as significant as those of the industry's inputs, the EF must be able to characterise impacts to ecological processes. Importantly, this must include ecological impacts downstream of the wastewater treatment process, in addition to the ecological impact of processes with the supply chain upstream of the water and wastewater treatment and distribution process.

The methodology described in this article addresses both these limitations by regionalising the input-output model that has previously supported national EF calculations, and by determing the area of disturbance caused by some environmental burdens not considered in the traditional EF model. In a first step, the regional input-output model determines indirect effects of water services activities in the form of point sources for a range of pollutants. Accuracy is improved by using "process data" where available to account for the direct environmental burden of the water service provider. The second step involves a nested fate model, which follows the fate of the point

source emissions at several spatial scales. The final output of this model can thus provide an indication of the direct and indirect burden connected with the water business, throughout its entire upstream supply chains. The accuracy of the input-output model is improved by the reconciliation of disparate data sources; calibrating concordance tables and employing optimisation techniques to deal with non-convergence.

2 Regionalising a Generalised Australian Input-output Model

The research team has regionalised the generalised input-output model that has previously supported national EF calculations (Lenzen & Murray, 2001; 2003). This regionalisation refers to the economic data published by the Australian Bureau of Statistics (Australian Bureau of Statistics, 2004), as well as accompanying existing physical data on land disturbance (Graetz *et al*., 1995; Lenzen & Murray, 2001) and greenhouse gas emissions (Australian Greenhouse Office, 1999), as well as additional physical data from the National Pollutant Inventory (National Pollutant Inventory, 2005). The final data set comprises:
- input-output data for 8 States[1] and 344 economic sectors[2];
- land use for 49 land types (see Table 1), by State and by economic sector;
- greenhouse gas emissions for 6 gases[3], by State and by economic sector;
- pollutant emissions for 86 contaminants[4], 3 compartments (air, water, soil), by State and by economic sector.

    An effort was made to adhere to the input-output table base year of 1998–99, but this was not possible where data sets were only available for neighbouring period. The physical data of the generalised input-output model is arranged in form of a matrix Q that measures the amount of environmental disturbance directly caused by a given economic sector during its on-site production of output. Rather than describing the entire physical dataset, we give an example for the land data only.

2.1 Example of Physical Data: the Land Database

From an environmental management perspective, the most comprehensive Australian land-use data set available today is the one generated by the National Land and Water Resources Audit (NLWRA), in collaboration with several Commonwealth, State and Territory agencies. It follows the Australian Land Use and Management Classification (ALUMC) (Bureau of Rural Sciences, 2001), which has been designed for users inter-

---

[1] New South Wales, Victoria, Queensland, Western Australia, South Australia, Tasmania, Northern Territory, Australian Capital Territory.
[2] These 344 are a subset of the sectors in the IOPC 8-digit classification, documented by the Australian Bureau of Statistics (2001a). The subset includes the non-confidential IOPC items.
[3] Carbon dioxide, methane, nitrous oxide, perfluorocarbons, sulphur hexafluoride, hydrofluorocarbons
[4] See www.npi.gov.au/about/list_of_subst.html for a current list of the 90 reportable substances. Note that for four substances (hexachlorobenzene, 2-methoxyethanol, 2 methoxyethanol acetate and 4,4'-Methylene-bis (2-chloroaniline)) no emissions have been reported.

Table 1: ALUMC land types available in the IRDB data set.

Primary Level	Secondary Level	Tertiary Level
Primary Level	Secondary Level	Tertiary Level
1.CONSERVATION AND NATURAL ENVIRON-MENTS	1.1. Nature conservation	1.1.1. Strict nature reserve 1.1.2. Wilderness area 1.1.3. National park 1.1.4. Natural feature protection 1.1.5. Habitat/species management area 1.1.6. Protected landscape 1.1.7. Other conserved area
	1.2. Managed resource protection	1.2.5. Traditional indigenous uses. 1.2.U. Unclassified
	1.3. Other minimal use	1.3.1. Defence 1.3.3. Remnant native cover 1.3.U. Unclassified
2.PRODUCTION FROM RELATIVELY NATU-RAL ENVIRONMENTS	2.1 Livestock grazing	2.1.0 Livestock grazing
	2.2. Production forestry	2.2.0 Production forestry
3.PRODUCTION FROM DRYLAND AGRICUL-TURE AND PLANTATIONS	3.1. Plantation forestry	3.1.0 Plantation forestry
	3.2. Farm forestry	3.2.0 Farm forestry
	3.3. Grazing modified pastures	3.3.0 Grazing modified pastures
	3.4. Cropping	3.4.1. Cereals 3.4.3. Hay and silage 3.4.4. Oilseeds and oleaginous fruit 3.4.5. Sugar 3.4.6. Cotton 3.4.8. Legumes
	3.5. Perennial horticulture	3.5.1. Tree fruits 3.5.3. Tree nuts 3.5.4. Vine fruits 3.5.U. Unclassified
	3.6. Seasonal horticulture	3.6.4. Vegetables and herbs
4.PRODUCTION FROM IRRIGATED AGRICU-LTURE AND PLANTA-TIONS	4.3. Irrigated modified pastures	4.3.0. Irrigated modified pastures
	4.4. Irrigated cropping	4.4.1. Irrigated cereals 4.4.3. Irrigated hay and silage 4.4.4. Irrigated oilseeds and oleaginous fruit 4.4.5. Irrigated sugar 4.4.6. Irrigated cotton 4.4.8. Irrigated legumes 4.4.U. Unclassified
	4.5. Irrigated perennial horticulture	4.5.1. Irrigated tree fruits 4.5.3. Irrigated tree nuts 4.5.4. Irrigated vine fruits
	4.6. Irrigated seasonal horticulture	4.6.4. Irrigated vegetables and herbs
5. INTENSIVE USES	5.4. Residential 5.7. Transport and communication 5.10. Intensive uses −Other	5.4.1. Urban residential 5.7.1. Airports/aerodromes 5.10.0 Intensive uses −Other
6. WATER	6.1. Lake 6.2. Reservoir 6.3. River 6.5. Marsh/wetland 6.6. Estuary/coastal waters	6.1.0 Lake 6.2.0 Reservoir 6.3.0 River 6.5.0 Marsh/wetland 6.6.0 Estuary/coastal waters
U.UNCLASSIFIED	5.10. Intensive uses −Other	5.10.0 Intensive uses −Other

ested in land management practices and outputs. It contains a three-tiered hierarchical structure designed in terms of the degree of intervention or potential impact on the natural landscape. The surface area of water is also included in the classification (see Table 1). As this classification has become the standard tool for the reporting of land use and management by Australian Government agencies, we have adopted it here as the standard tool for analysing and reporting land use in our EF calculations.

The NLWRA data set is published as the Integrated Regional Database (IRDB), and provides the hectares of land-use of a given ALUMC type in a given Statistical Local Area (SLA) of Australia (Australian Bureau of Statistics, 2001c). SLAs generally correspond to local government areas (LGAs), with a number of exceptions including urban environments where a large number of people may live in one LGA and the SLA is a smaller collection of suburbs (Australian Bureau of Statistics, 2001d). However, in order to include this land-use information into our generalised input-output model we also need to know which economic sectors are the main users of that piece of land and how they share it. Identification of the main users of a given land type in a given region has been carried out applying basic knowledge of the industrial activities of the various economic sectors in Australia and its relation with the ALUMC land types. Land shares have been assigned to economic sectors on the basis of their employment, using the Australian Business Register (Australian Bureau of Statistics, 2001 b).

As with most data sets, the land-use data from the IRDB is incomplete and there are many land type-SLA cells for which data is missing. Furthermore, the group of land types reported in the data set is only a subset of the complete array of land types in Australia. The list of the ALUMC land types available in the IRDB data set (together with the added unclassified categories) is shown in the Table 1.

2.2 Disaggregating national physical data by State and by detailed industry sector

Before embarking on potentially protracted computations an integration strategy was designed. Based on available data, this strategy involved considering:
- The aspired level of overall sectoral detail;
- Proportionality assumptions underlying pro-rata techniques;
- The degree of inconsistency in the raw data;
- Concordances between different classification systems; and
- Balancing methods to be employed.

2.2.1 Choice of level of sectoral detail
The standard classification used in Australia and New Zealand for the collection, compilation and publication of various statistics by economic sector is the Australian and New Zealand Standard Industrial Classification, ANZSIC. In its most disaggregated form it contains 465 industrial classes labelled by a 4-digit code (ANZSIC4). On the other hand, the industrial classification used in the Australian input-output tables is the Input-Output Industrial Classification, IOIC. The IOIC consists of about 106 economic sectors (depending on the publication year) and it is based on ANZSIC, though redefined to eliminate secondary or subsidiary production. Additional commodity information included in the Australian input-output tables is given using the 8-digit unpub-

lished version of the published 4-digit Input-Output Product Classification, (IOPC4 and IOPC8; Australian Bureau of Statistics, 2001a), defined in terms of the characteristic products of industry sectors. In our economic model, we use a classification consisting of 344 sectors defined as a subset of IOPC8 items and labeled by a 7-digit code (called ISAPC).

A major task before any disaggregation was to prepare concordance tables between ISAPC and ANZSIC4, ALUMC and the National Greenhouse Gas Inventory (IPCC classification – Intergovernmental Panel on Climate Change). Concordance tables were "calibrated" using data known in both classifications, for example business turnover / gross output, and employment (Australian Bureau of Statistics, 1998; 2001 b).

The classification of the National Greenhouse Gas Inventory (NGGI), for example, is even more aggregated than the published IOPC4 input-output system. The integration of the NGGI into an input-output framework would be straightforward if the input-output model was aggregated to NGGI level. This reduction in resolution however would severely limit the capabilities of the resulting model for impact analysis and decision-making. Especially, if additional indicators (pollutants, downstream impacts, etc) are to be integrated into a comprehensive EF accounts system, it is desirable to compile the framework at the maximum level of detail, and aggregate the results after impact analysis if necessary.

Working at a high level of detail is desirable because it is likely that physical data on different indicators contains varying detail for different industry sectors. For example, energy data is likely to be detailed for energy-intensive metal sectors, while employment data is likely to be detailed for service sectors, both of which often do not feature detailed water use data. A consequence of this strategy is that some disaggregation can be achieved only through prorating according to proxy variables. Such prorated data is of course not very accurate. However, sectors affected by prorating are also not likely to be important in terms of their contribution to overall flows. Hewings *et al*., (1988) showed that large uncertainties occurring even in a large number of small elements of input-output tables hardly affect the magnitude of multipliers. Hence, there is no penalty in keeping a large number of uncertain but small data, as long as important (large) data items are sufficiently accurate, and as long as uncertain data are either aggregated or clearly marked in the presentation of subsequent impact analysis results.

A practical example may highlight the importance of working at the highest possible detail: consider the embodied emissions passed on from bauxite mining to aluminium smelting. Assume that bauxite mining was aggregated with gold mining operations, which need less water, and that gold processing was part of the non-ferrous metal sector, together with aluminium processing. In an aggregated framework, considerable embodied emissions would be passed on to gold processing, even though gold mining used only little water per dollar of output. In a disaggregated analysis, these embodied emissions would only affect aluminium. Even if both sectors were aggregated after impact analysis, the results would be different from those of an aggregated impact analysis, because of the different downstream sales structures of bauxite and gold mining.

Table 2: Example integration procedure: National Greenhouse Gas Inventory by ISAPC

A) Estimate Gross State Output (GSO) data by IS-APC:	Extract number of business locations by State by turnover range by ANZSIC from the 2001 Business Register (Australian Bureau of Statistics, 2001b),
	Estimate not provided ("n.p.") entries using RAS,
	Estimate (unknown) turnover by State by ANZSIC from (known) number of business locations by turnover range, by fitting a piece-wise continuous, strictly positive business-number-density functions consisting of quadratic and cubic spline functions across discrete turnover ranges, and finally integrating these density functions over turnover,
	Calibrate an ISAPC–ANZSIC concordance matrix using existing turnover / gross output data in ANZSIC and ISAPC for the whole of Australia, and apply this concordance matrix to State data.
B) Estimate employment by State by ISAPC:	Extract employment by State by ANZSIC from the 1998 Business Register ([Australian Bureau of Statistics, 1998),
	Estimate not provided ("n.p.") entries using RAS,
	Calibrate a new ISAPC–ANZSIC concordance matrix using employment data classified in ANZSIC and ISAPC for the whole of Australia, and apply this concordance matrix to State employment data.
C) Estimate material flow data by State by ISAPC:	Extract material flow data from the 2004 Commodity Statistics (Australian Bureau of Agricultural and Resource Economics, 2004).
D) Create an initial estimate for greenhouse gas emissions by State by IS-APC:	Use material flow, GSO, and employment data as proxies for prorating aggregate greenhouse gas emissions across primary, secondary and tertiary ISAPC sectors.
E) Reconcile this initial estimate with all available constraints derived from survey data:	Use the NGGI and additional reports (George Wilkenfeld & Associates Pty Ltd and Energy Strategies, 2002) to formulate constraints on the detailed ISAPC accounts, and use these constraints as an input for a RAS balancing routine.
	RAS–balance the initial estimate based on constraints on total sums over greenhouse gas emissions by sector, and by State, or based on sub-totals over certain sectors; terminate RAS when results do not converge any further, that is, when conflicting constraints cause oscillation.
	Apply optimisation to find the best compromise between conflicting constraints, based on uncertainty of the survey data. For example, if for a certain subtotal, one constraint prescribes a value of 50 t ± 10%, and another constraint prescribes 70 t ± 25%, the optimised constraint may be 55 t.

2.2.2 Data inconsistencies and balancing methods

Many of the physical data sets available in Australia are conflicting, due to sampling and/or rounding errors, or due to differences in definitions or base years. For example, energy data by State, industry sector, fuel type and equipment type (Australian Bureau of Agricultural and Resource Economics, 1999) may add up to different subtotals, depending on whether sums over States, equipment types, fuel types, or sectors. Data

often refer to different years. Strictly speaking, a temporal misalignment of surveys calls for a simultaneous balancing procedure of all data over all periods, imposing certain temporal stability conditions (compare Tarancon & Del Rio, 2005).

Conflicting data causes conventional RAS balancing techniques (Gretton & Cotterell, 1979) to oscillate, thus preventing convergence. The more serious the data discrepancies, the more imperfect the final RAS result. Such non-convergence can only be dealt with using optimisation techniques. These techniques have been the subject of recent articles in the expert literature, and shall not be dealt with further here.

The challenges of a practical integration procedure are perhaps best illustrated using a real-world example. Creating greenhouse gas accounts for all Australian States and Territories at the ISAPC sectoral detail requires the actions given in Table 2.

The procedure sketched above may give a feeling about how involved the reconciliation of more than two or three disparate data sources can be. A number of issues require further attention[5].

2.3 Enhancing geographical resolution from States to Statistical Local Areas

After integration of the physical and economic data into one regional input-output framework, the usual input-output calculus is followed, including calculating:

- the direct requirements matrix $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ from the regional input-output coefficient table $\mathbf{T}$ and diagonalised Gross State Output $\hat{\mathbf{x}}$;
- the physical coefficients matrix $\mathbf{q} = \mathbf{Q}\,\hat{\mathbf{x}}^{-1}$;
- the Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$;
- generalised multipliers $\mathbf{q} \# \mathbf{L}$, where $\#$ denotes element-wise multiplication.

Import and exports from the Australian economy are taken into account-for further details on these procedures see Lenzen (2001). Let element q_{ij}^r describe the EF impact of type i (land type, emissions type) caused by industry sector j in State r. Let element L_{jk}^{rs} describe the gross output of industry sector j is State r necessary to satisfy final demand from industry sector k in State s. Then $(q\#L)_{ijk}^{rs} = q_{ij}^r\,L_{jk}^{rs}$ is the impact of final demand from industry sector k in State s in terms of the EF of type i caused by industry sector j in State r. The Australian Business Register (Australian Bureau of Statistics, 1998; 2001b) contains employment e_j^{rs} size and business counts b_j^{rs} by industry sector j in r_n Statistical Local Areas (SLAs) in State r. Using this knowledge of which industries actually occur in the 1322 Australian SLAs, the EF can be broken down into SLA regional detail by assuming that the gross output L_{jk}^{rs} required from industries j in State

---

[5] Firstly, in theory there should be only one concordance matrix between two classification systems, for example ISAPC and ANZSIC. However, attempts to estimate such a matrix using cross-calibration of two national datasets (turnover and employment) generated two substantially different concordance matrices, hence either employment and/or turnover in one or both systems must include significant errors. Secondly, RAS techniques do not work when data conflict. Often, analysts trace inconsistencies manually, and/or make subjective selections based on data quality. Optimisation techniques can assist previously manual adjustments to conflicting survey data. Faced with problems such as these, an effort could be made to streamline data collection by using only one classification system. The lack of such harmonisation is ubiquitous, not only in Australia, and has been deplored by analysts for some time (Jones et al, 1994).

r is distributed homogeneously across all industries of type j in subregions r_n of State r, for example according to their employment size:

$$(q\#L)_{ijk}^{rns} = q_{ij}^{r} L_{jk}^{rs} \frac{e_j^{rm}}{\sum_m e_j^{rm}}$$

While this enhancement of the geographical resolution of the regional input-output model (States and Territories) to Statistical Local Areas is not supported by local input-output data, it facilitates an improved approach to modelling the area disturbed as a result of point source emissions of a wide range of pollutants.

# 3 Modelling Environmental Burdens Due To Emissions

The calculations to improve the regionalisation of the input-output procedure for the calculation of an EF outlined above may be used to produce an emission matrix that includes the direct onsite impacts-an improved approach to modelling areas disturbed as a result of point source emissions, as shown in Figure 1.

Fig. 1: General calculation process for the novel EF
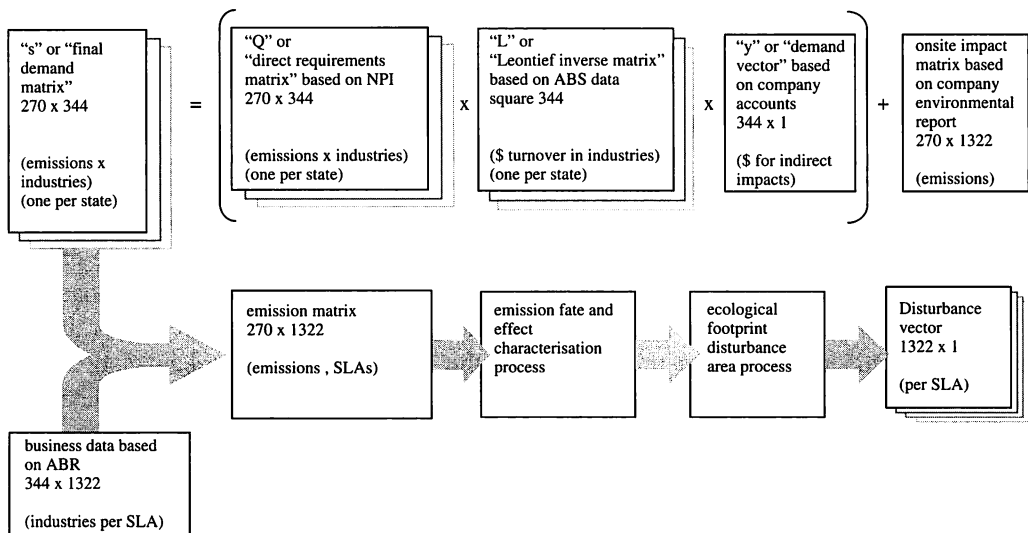
This is what might be called a "hybrid approach" to EF calculation – obtaining improved accuracy by using "process data" where available to account for the direct environmental burden of a water service provider, and adding this to input-output calculations to provide an indication of the burden of upstream units in the supply chains connected with the service provider (Peters *et al.*, 2006). Process data is considered more accurate for the estimation of environmental burdens caused directly by a service provider (eg.: Peters and Lundie, 2002; Lundie *et al.*, 2004), but it is impractical to collect data for the entire supply chain, hence the interest in using input-output analysis to cope with the indirect disturbance due to economic activities further up the supply

Fig. 2 Conceptual representation of a Mackay level III fugacity model in USES 4.0 (adapted from RIVM, VROM, VWS, 1998)
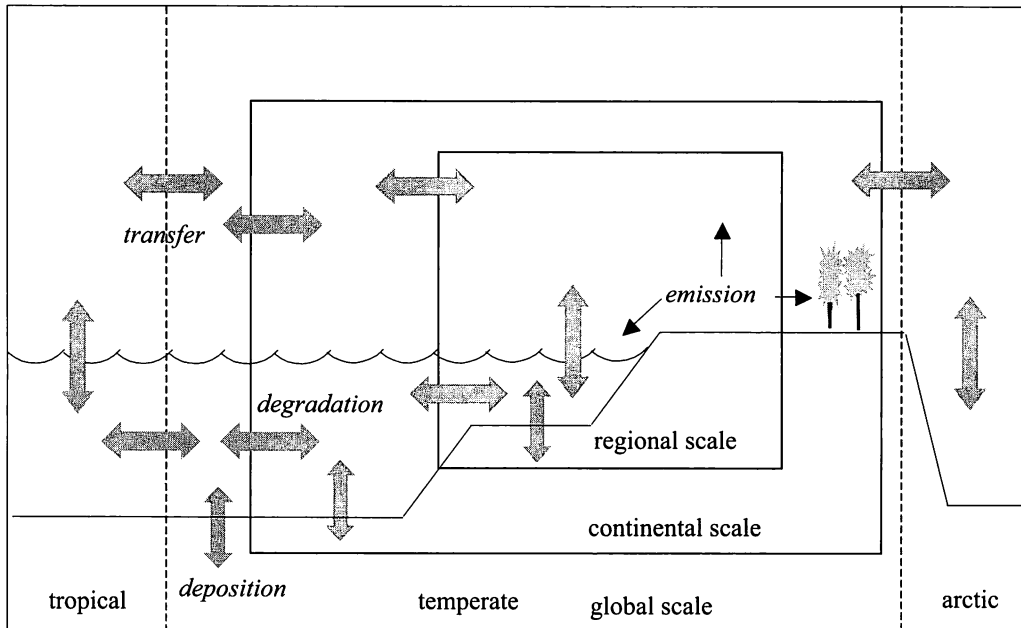
chain. Combining the areas disturbed directly by the service provider and the indirect disturbances gives an idea of the total surface area of the earth, which is disturbed in order to support the service provider.

In addition to this inclusion of local environmental effects we wish to further improve the EF method, by enhancing its environmental scope. Previous calculations of the EF of Australian water service providers have only considered land directly or indirectly demanded by resource-producing activities or disturbed by climate change effects due to greenhouse gas emissions. Here we propose a novel extension of the impact assessment process consistent with previous methodology to include toxic effects due to emissions. This will be used to characterise the emission both upstream and downstream of the water service provider's processes. We also develop a more complete calculation of direct disturbances.

3.1 Characterisation of emissions

In order to include the toxic effects of emissions to air, land and water, a modelling approach must be sophisticated enough to cope with the variable residence time of contaminants in these environmental compartments, their transport between them and their ultimate potential to cause environmental damage. To be of practical use as an environmental management and reporting tool within industry, it must be simple enough to operate on an ordinary personal computer and provide instant results. This rules out the possibility of the construction of dynamic models given the large number of contaminants (270) which would require simultaneous fate simulation involving mass transfer, reaction, sorption, degradation and other environmental processes in a large number of

locations (1322). A simpler approach had to be adopted based on the idea of steady-state multi-compartmental modelling to compute contaminant characterisation factors that could be loaded into an EF calculator.

Fortunately the need for such an approach has previously been recognised by environmental life cycle assessment practitioners and governments concerned with priority setting for environmental health, and the concept has been extensively developed by European and American researchers (eg : Huijbregts *et al.*, 2000; Bare *et al.*, 2003). The leading European model, Uniform System for the Evaluation of Substances (USES) was originally developed by a whole-of-government effort in the Netherlands (RIVM *et al.*, 1998), and continues to be updated and improved (RIVM *et al.*, 2002). It has also been adapted for Australian environmental conditions by Huijbregts *et al.*, (2003).

Consistent with its Canadian and European predecessors (Mackay, 1991; RIVM *et al.*, 1998) this involves the construction of a nested fate model, which follows the fate of an emission at several spatial scales. As shown conceptually in Figure 2, the model considers transfer functions between different environmental compartments and different frames of spatial reference. More recently the usefulness of this approach has been further improved by the calculation of characterisation factors based on emissions in several different Australian situations: urban air; rural air; agricultural soil; industrial soil; and freshwater and marine environments (Lundie *et al.*, 2005). By using GIS software we are able to associate appropriately location-specific characterisation factors of these types to individual SLAs. This is similar to the approach taken to regional impact characterisation in Japan in recent work by Nansai *et al.*, (2005).

A marginal change in the steady-state concentration of a contaminant emitted in each of the relevant environmental compartments is considered by the calculation of compartment specific fate factors of the form:

$$F_{j,i,s} = \frac{\partial C_{j,s}}{\partial M_{i,s}}$$

where $F_{j,i,s}$ is the compartment-specific fate factor that accounts for the transport efficiency of substance s from compartment i to and persistence in compartment j (year. m^{-3}), $\partial C_{j,s}$ is the marginal change in the steady state dissolved concentration of substance s in compartment j (kg.m^{-3}), and $\partial M_{i,s}$ is the marginal change in emission of substance s to compartment i (kg.year^{-1}). It has been previously shown by van de Meent and Huijbregts (2005) that chemical effect factors may be calculated on the basis of toxicity data using the formula:

$$E_{j,s} = \frac{\partial msPAF_j}{\partial C_{j,s}} \approx 0.7 \cdot \frac{1}{HC\,50_s}$$

where $E_{j,s}$ is the effect factor of substance s for compartment j (m^3.kg^{-1}), $\partial msPAF_j$ is the marginal change in the potentially affected fraction of species due to exposure to a mixture of chemicals in compartment j , and $HC50_s$ is the hazardous concentration of substance s where 50 percent of the species is exposed above an acute or chronic toxic value (kg.m^{-3}). On this basis, where $CF_{j,i,s}$ is the characterisation factor for contaminant s emitted in compartment i on compartment j, it is possible to calculate:

$$CF_{j,i,s} = F_{j,i,s} \cdot E_{j,s}$$

Finally, where f_j is the area fraction of compartment j in environment e, compartment-specific factors are aggregated into an environment-specific characterisation factor:

$$CF_{e,s,i} = \sum_{jee} CF_{j,i,s} \cdot f_{jee}$$

This approach differs from many previous approaches to characterisation factor calculation, which did not explicitly consider fate modelling or were expressed as an effect ratio to an equivalent substance, analogous to the carbon-dioxide equivalents in common use for characterisation of different types of greenhouse gas emissions. The current approach to characterisation factor calculation is described in greater detail by Lundie *et al* (2007). The benefits of this approach for EF calculation become apparent in the ease with which a disturbance area can be calculated.

3.2 Including direct local environmental burdens

To include the direct onsite impacts associated with a water service provider's operations within a regionalised EF we take the hybrid approach. We propose that land directly occupied by water service providers is carried through the matrix algebra unmodified as usual, but we also allow the water business to use data which may exist on the area of water bodies directly disturbed by it. For example, Sydney Water has performed extensive research to determine the scale of the typical "mixing zone" offshore where the concentration of scheduled substances is exceeded prior to dilution (Sydney Water, 1998). The area of the ocean burdened in this way is entered into the model and carried through in the same way as the directly burdened land area.

The application of biosolids as a soil additive has beneficial effects for soil organic matter and other factors in productivity, but it also results in very small quantities of unwanted contaminants being deposited on agricultural land. The application of biosolids is therefore characterised using the factors described in 3.1 to provide a fractional disturbance intensity of the areas over which the biosolids are deposited. This will require some data collected by water authorities on biosolids application to be entered into the model. These disturbance areas are added to the land disturbance due to the direct land use of upstream businesses as part of a total land disturbance calculation.

3.3 Disturbance area calculation

Annual emissions in an SLA estimated in kg/year by the hybrid input-output methodology are characterised by multiplication by the appropriate characterisation factor described in Section 3.1. Having characterised an emission of a particular substance, EF calculation requires the results to be expressed in a real terms. Unlike previous approaches to emission characterisation based on the use of a reference substance such as dichlorobenzene (Guinee *et al.*, 2002), characterisation using the new Australian factors produces a dimensionless result. This result reflects the intensity of the impact caused by emissions from that SLA. A dimensionless result is consistent with the approach taken by Lenzen and Murray (2001) which allows for the intensity of land disturbances

caused by different degrees of change in landuse to be characterised. The intensity of disturbances caused by several emissions can be aggregated into a total disturbance per SLA. Partially disturbed areas can be aggregated on the basis of the aggregated disturbance intensity and the area of the disturbed environment to produce a total Australian EF, as shown in the equation:

$$D_{total} = D_{direct} + \sum_e \sum_s \sum_i CF_{e,s,i} \cdot m_{s,i} \cdot A_e$$

where D_{direct} is obtained from the onsite impacts matrix (see Figure 1), $m_{s,i}$ is the annual emission of contaminant s to compartment i and A_e is the area of the effected environment.

Another point of consistency between this process and previous developments in disturbance-based EF methodology is that, similar to the approach of Lenzen and Murray (2001) to greenhouse gas emissions, the responsibility for damages outside a geographic area caused by emissions from that area, remain associated with the emitting area. Therefore, in addition to the national EF calculation, the novel EF methodology enables the user to compare the EF of an SLA with the actual SLA area.

4 Example calculation

As an imaginary example, let us assume that annual emissions of benzene to air, water and soil from various industries located on the urbanised coastal fringe of Australia were 1200000, 50000 and 110 kg respectively. The relevant characterisation factors $CF_{e,s,i}$ for benzene (= s) as presented in Lundie et $al.$, (2007) are shown in Table 3.

Table 3: Example characterisation factors (kg/yr)

		Impacted environmental compartments 'e'		
		Freshwater	Marine	terrestrial
Emission compartments 'i'	urban air	2.3×10^{-14}	1.6×10^{-16}	3.8×10^{-15}
	marine water	2.6×10^{-15}	7.4×10^{-15}	4.0×10^{-16}
	industrial land	3.9×10^{-12}	1.1×10^{-16}	4.8×10^{-12}

If we were considering emissions in an inland location we would chose the characterisation factors for freshwater instead of marine water, as the aquatic emission compartment would be different. Similarly, rural air and agricultural land might be more appropriate — the actual location of the source of the emission would determine this. To calculate the disturbance area in each of the impacted environmental compartments we multiply the given emissions by the characterisation factors and the areas of the impact compartments (A_e) which are taken as 6×10^6, 2.5×10^8 and 77×10^8 ha for freshwater, marine and terrestrial ecosystems, respectively. This produces the results shown in Table 4.

In this example the total disturbance area is 4.3 ha. The emissions to each of the compartments listed makes some contribution to the total figure but it is dominated by

Table 4: Example disturbance areas (ha)

		Impact environmental compartments 'e'		
		Freshwater	Marine	terrestrial
Emission compartments 'i'	urban air	1.6×10^{-1}	4.8×10^{-2}	3.5
	marine water	7.8×10^{-4}	9.3×10^{-2}	1.5×10^{-2}
	industrial land	2.6×10^{-3}	3.0×10^{-6}	4.1×10^{-1}
Total areas		**1.7×10^{-1}**	**1.4×10^{-1}**	**4.0**

the relatively large emissions to air and the relatively greater effect of benzene on the terrestrial environment. This is just an example calculation intended to illustrate how this extension of disturbance-based ecological footprint methodology works. The key issue illustrated is that in contemporary ecological footprint calculations, this component of the total footprint is ignored-set at zero. For example, while the use of pollution control equipment to minimise such benzene emissions may have ecotoxicological benefits, existing methodologies are insensitive to them, and the consumption of energy by the equipment with the consequent greenhouse gas production will always cause a finite, positive ecological footprint to be calculated, irrespective of the reduced toxic emissions. Future papers will examine specific case studies in depth.

5   Implementing the novel EF across the Australian Water Industry

The aim of this research has been to develop a novel EF concept to be applied at the company level to any Australian urban water services provider. The research addresses major methodological limitations of the existing national EF concept by using a hybrid of regionalised input-output analysis and a nested fate model. This proposed EF methodology improves on previous EF methodologies by avoiding exclusive reliance on national average environmental and economic data, and by allowing toxicants to be included in a disturbance-based calculation analogous to the established inclusion of greenhouse gases in EF. By making it more comprehensive and quantitative, the new method should be a more effective environmental reporting and communications tool for the Australian water industry and allow the water industry to benchmark across sectors. Furthermore, being a generic approach to environmental reporting, it may potentially be applied by any economic entity that can present accurate financial and process data. To demonstrate the effectiveness of this method will in practice require testing by various water authorities in Australia.

5.1   Data Requirements

We have attempted to strike a workable compromise between making excessive use of assumptions about a water service provider's operations and a requirement for excessive data acquisition and pre-processing by the water service provider in order to use this technique. This section briefly lists the information that the model will require from the water service provider.

The calculation of the "upstream emissions" – those that result from an organisation's purchase of goods and services, will require the water service provider to supply the following data:
- An annual expenditure account ($);
- An annual revenue account ($).

The calculation of the "downstream emissions", physical emissions from the premises of the authority in question, will require the following annual environmental reporting data:
- Greenhouse gas emissions – carbon dioxide and (unflared) methane (standardised according to the Water Services Association Australia (WSAA) Greencount calculator);
- The provider's last National Pollutant Inventory (NPI) submission or equivalent data;
- The provider's biosolids product rate, typical contaminant specifications and a geographical descriptor (postcode or LGA) for where the biosolids were applied.

The water service provider will also need to estimate the land directly disturbed by its operations. This is done by estimating the area land managed by the authority, and the degree to which its operations have changed it from its natural state – for example, catchment lands are considered undisturbed by the water authority, whereas a block predominantly covered with concrete by construction of a sewage treatment plant would be 100% disturbed. A standardised approach to this estimation is already emerging though the practical application the EF within the Australian water industry.

5.2 Conclusions

We have developed a new method for calculating EFs. This method considers the disturbance area caused by human activities at a finer level of geographical disaggregation than previously – we have driven the area considered from the nation down to 1322 smaller regions ("Statistical Local Areas"). The method also addresses a previous weakness in disturbance-based EF calculation – its blindness to ecotoxic emissions. As the paper illustrates, these may contribute a finite area to future EF calculations, and avoid the current theoretical problem whereby pollution control activities increase the calculated EF without taking into account the benefits of reduced ecotoxicity burdens on the environment.

To ensure the most effective transfer of this research to industry practice a number of areas need to be addressed. While the development of a more rigorous EF methodology should result in wider acceptance by stakeholders and the community, the scalability of the methodology for application by both large and small urban water service providers operating in different geographical and regulatory environments needs to be tested and stakeholder requirements of the novel EF methodology need to assessed. In particular, the manner in which the regionalised and compartmentalised data is best presented, needs to be established.

A program of practical research is planned to demonstrate that the novel hybrid EF methodology can deliver in these areas. By a combination of data trials, software development and social research, the research program will ensure that the methodol-

ogy is neither too scholastic to be employed by water industry practitioners or communicated to water industry stakeholders nor too pragmatic to undermine its academic or regulatory credibility.

References

Australian Bureau of Agricultural and Resource Economics (1999) *Australian energy consumption and production*, ABARE Research Report 99.4 (Commonwealth of Australia, Canberra, Australia).

Australian Bureau of Agricultural and Resource Economics (2004) *Australian Commodity Statistics*, ABARE project 1059 (Australian Government, Canberra, Australia).

Australian Bureau of Statistics (1998) *Business Register Counts 1998*, Customised Report No. 98/ (Australian Bureau of Statistics, Canberra, Australia).

Australian Bureau of Statistics (2001a) *Australian National Accounts, Input-Output Tables, Product Details, 1996–97*, ABS Catalogue No. 5215.0 (Australian Bureau of Statistics, Canberra, Australia).

Australian Bureau of Statistics (2001b) *Business Register Counts 2001*, Customised Report No. 01/ (Australian Bureau of Statistics, Canberra, Australia).

Australian Bureau of Statistics (2001c) *Integrated Regional Data Base*, Electronic database (unpublished) (Australian Bureau of Statistics).

Australian Bureau of Statistics (2001d) *Statistical Geography, Vol1. Australian Standard Geographical Classification (ASGC)*. ABS Catalogue No. 1216.0. (Australian Bureau of Statistics, Canberra, Australia).

Australian Bureau of Statistics (2004) *Australian National Accounts, Input-Output Tables, 1998–99*, ABS Catalogue No. 5209.0 (Australian Bureau of Statistics, Canberra, Australia).

Australian Greenhouse Office (1999) *Australia's National Greenhouse Gas Inventory*, www.greenhouse.gov.au/inventory accessed March 2006 (Australian Greenhouse Office).

Bare J.C., Norris G.A., Pennington D.W., McKone T. (2003) TRACI The Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts. Journal of Industrial Ecology, 6(3–4)49–78.

Sack, F., Bransgrove G., Charet L., Peters, G, (2003) *A Large Metropolitan Water Supplier – Steps to Sustainability*. (Proceedings of OzWater Conference of the Australian Water Association, 6–10 April 2003, Perth Australia.)

Bureau of Rural Sciences (2001) *Land Use Mapping at Catchment Scale: Principles, Procedures and Definitions*, Edition 1 (Bureau of Rural Sciences, Canberra, Australia).

Chambers N., Lewis K. (2001) *Ecological Footprint Analysis– Towards a Sustainable Business Indicator* Association of Certified and Chartered Accountants (UK)ACCA Research Report No.65 Certified Accountants Educational Trust, London.

George Wilkenfeld & Associates Pty Ltd & Energy Strategies (2002) *Australia's National Greenhouse Gas Inventory 1990, 1995 and 1999 – end use allocation of emissions*, (Australian Greenhouse Office, Canberra, Australia).

Guinee J.B. (2002) *Handbook on Life Cycle Assessment – Operational Guide to the ISO Standards*, p.576–596. Kluwer Academic, Dordrecht, The Netherlands.

Graetz, R. D., Wilson, M. A., Campbell, S. K. (1995) *Landcover disturbance over the Australian continent*, Biodiversity Series, Paper No. 7 (Department of the Environment, Sport and Territories Biodiversity Unit, Canberra, Australia).

Gretton, P., Cotterell, P. (1979) The RAS method for compiling input-output tables – Austra-

lian Bureau of Statistics experience, in: *Eighth Conference of Economists* (La Trobe University).

Hewings, G. J. D., Sonis, M. Jensen, R. C. (1988) Fields of influence of technological change in input-output models, *Papers of the Regional Science Association*, 64:25–36.

Huijbregts M.A.J., Thissen U., Guinee J.B., Jager, T., Kalf D., van de Meent D., Ragas A.M. J., Wevener Sleeswijk A., Reijnders L. (2000). Priority assessment of toxic substances in life cycle assessment. Part 1: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES–LCA. *Chemosphere*, 41, 541–573.

Jones, B. P., Peng, Z. –Y., Naughten, B. (1994) Reducing Australian energy sector greenhouse gas emissions, *Energy Policy*, 22(4), pp. 270–286.

Lenzen, M. (2001) A generalised input-output multiplier calculus for Australia, *Economic Systems Research*, 13(1), pp. 65–92.

Lenzen, M., Lundie S., Bransgrove G., Charet L., Sack F. (2003). Assessing the EF of a large metropolitan water supplier – lessons for water management and planning towards sustainability. *Journal of Environmental Planning and Management* 46(1)113–141.

Lenzen, M., Murray, S. A. (2001) A modified ecological footprint method and its application to Australia, *Ecological Economics*, 37(2)229–255.

Lenzen, M., Murray, S. A. (2003) *The ecological footprint – issues and trends*, ISA Research Paper 01–03, www.isa.org.usyd.edu.au/publications/documents/Ecological_Footprint_Issues_and_Trends.pdf accessed March 2006 (The University of Sydney, Sydney, Australia).

Levett, R. (1998) Footprinting: a great step forward, but tread carefully, *Local Environment*, 3(1), pp. 67–74.

Lundie S., Huijbregts M.A.J., Howley H.V., Mohr N.J., Feitz A.J. (2007) Australian characterisation factors and normalisation figures for human toxicity and ecotoxicity. *Journal of Cleaner Production*, 15:819–832.

Lundie S., Peters G.M., Beavis P. (2004) Life cycle assessment for sustainable metropolitan water systems planning. *Environmental Science and Technology*, 38,3465–3473.

Mackay D. (1991) "Multimedia Environmental Models; The Fugacity Approach" Lewis Publishers, CRC Press, Baton Roca.

Nansai K, Moriguchi Y, Suzuki N. (2005) Site-dependent life-cycle analysis by the SAME approach: its concept, usefulness and application to the calculation of embodied impact intensity by means of an input-output analysis. *Environmental Science and Technology*, (in press).

National Pollutant Inventory (2005) *Australia's national database of pollutant emissions*, http://www.npi.gov.au/ http://www.greenhouse.gov.au/inventory accessed March 2006 (Department of the Environment and Heritage).

Peters G.M., Rowley H.V., Lundie S., Flint M. (2006) Challenges and opportunities in LCA – the water industry example. Proceedings of the 5th National Conference of the Australian Life Cycle Assessment Society, 22–25 November, Melbourne, Australia.

Peters G.M., Lundie S. (2002) Life-cycle assessment of biosolids processing options. *Journal of Industrial Ecology*, 5(2)103–121.

O'Dwyer, E. (2006) Can the planet sustain your lifestyle? Sydney Morning Herald, 17 December 2006, www.smh.com.au accessed 17 December 2006.

Opschoor, H. (2000) The ecological footprint: measuring rod or metaphor?, *Ecological Economics*, 32, pp. 363–365.

RIVM, VROM, VWS (1998) Uniform System for the Evaluation of Substances. National In-

stitute of Public Health and the Environment (RIVM), Ministry of Housing, Spatial Planning and the Environment (VROM), Ministry of Health, Welfare and Sports (VWS), the Netherlands.

RIVM, VROM, VWS (2002) Uniform System for the Evaluation of Substances 4.0 (USES 4.0). National Institute of Public Health and the Environment (RIVM), Ministry of Housing, Physical Planning and the Environment (VROM), Ministry of Health, Welfare and Sports (VWS), the Netherlands.

Sydney Water Corporation (1998) Ecological and human health risk assessment of chemicals in sewage overflows in the Sydney-Blue Mountains-Illawarra Regions [Variant title: Ecological and human health risk assessment of chemicals in wet weather sewage over-flows in the Sydney, Blue Mountains, Illawarra Regions] (Sydney Water Corporation, Sydney, Australia).

Tarancon, M., Del Rio, P. (2005) Projection of input-output tables by means of mathematical programming based on the hypothesis of stable structural evolution, *Economic Systems Research*, 17(1)1−23.

van de Meent D., Huijbregts M.A.J. (2005) Calculating life-cycle assessment effect factors from potentially affected fraction-based ecotoxicological response functions. *Environmental Toxicology and Chemistry*, 24(6)1573−1578,

van den Bergh, J. C. J. M., Verbruggen, H. (1999) Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint', *Ecological Economics*, 29(1)61−72.

van Kooten, G. C., Bulte, E. H. (2000) The ecological footprint: useful science or politics?, *Ecological Economics*, 32: 385−389.