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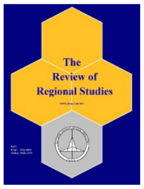

Physical Water Use and Water Sector Activity in Environmental Input-Output Analysis*

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Abstract: This paper uses input-output accounting methods to identify the direct, indirect, and induced physical demand for water. The seminal work by Leontief (1970) has previously motivated a more extensive account of issues related to those sectors that generate and those that clean/treat polluting outputs. The present paper extends this approach to deal with sectors that use a natural resource and those that supply it. We take, as a case study, public water use and supply in Wales. The analysis shows how the proposed method, using both the quantity input-output model and the associated price dual, can be used to investigate the economy-wide implications of the deviation between expenditures on the output of the water sector and actual physical water supplied. The results indicate that the price paid for water varies greatly amongst different uses; in particular, household consumption is charged at a higher price than intermediate industrial demand. We argue that decision makers (in this case, policy makers and industry regulators) require such analysis and information in order to understand the demands on and supply of water resources and their role in supporting economic expansion, whilst simultaneously adopting appropriate strategies for achieving water sustainability objectives.

JEL Codes: C67, Q25, R11

Keywords: water resources, full Leontief environmental model, input-output, multipliers, Wales

1. INTRODUCTION

Water policy and regulation in the United Kingdom and its devolved administrations increasingly prioritize efficient use of the resource and recognize competing uses for scarce water resources within an ecosystems services framework (see for example, DEFRA (2016)). In terms of both the potable and unpotable supply to households and firms, policy and

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regulation are having to respond to issues such as increases and changes in the spatial distribution of water demands. They also need to consider the more implicit environmental costs associated with water abstraction and use within individual water catchments. For example, current water regulations across the UK require the water companies to incorporate a specific Water Resources Management Plan (WRMP) that takes into account the planning processes, strategies, and action for enabling a more resilient water sector (Welsh Government, 2016). This type of planning recognizes that industrial and household demands might lead to unsustainable water abstraction levels and associated water stress. Water companies and regulators therefore face the challenge of comprehending the complex economic interactions determining water use, particularly public water supply use, and the sustainability of this supply (Environment Agency, 2015). One critical aspect is better mapping and understanding how changes in water demand in one part of the economy, or one sector, affects water use in other parts of the economy, which implies identifying the levels of water that are embedded in industry supply chains.

This paper demonstrates the way in which environmental input-output methods can be used to improve our understanding of the economy-wide implications of using water resources to meet economic needs (Leontief, 1970; Allan et al., 2007b). The intention is to assist stakeholders in understanding how changes in the size and industrial composition of regional production will affect future patterns of industrial water demand and impact infrastructure needs within water catchments. A valuable tool in this procedure is the use of water multipliers which link direct, indirect, and, where appropriate, induced water use to industrial activity. In fact, the proposed method using both the quantity input-output model and the associated price dual can be used to consider the implications of the deviation between expenditures on the output of the water sector and actual physical water supplied. In doing so, we provide insights regarding which types of industries and consumers ultimately bear the costs of provision. We consider how this might not be fully incorporated into the market prices of industrial outputs. This has basic implications for policy such as correctly identifying pressures on water supply that would occur through the expansion of particular sectors.

The remainder of the paper is structured as follows. Section 2 reviews early developments in environmental input-output modelling. Section 3 gives a step-by-step account of how insights from the Leontief (1970) generalized model can be applied to the demand for, and the supply of, a physical resource such as water. Section 4 describes the data used in this application and the adjustments to input-output coefficients required to reflect the differences between payments actually made to the water sector and those implied by actual water use. Section 5 outlines the main findings of the analysis, focusing on their implications for analyzing water resource use within an input-output framework and for guiding policymakers. Section 6 concludes.

2. WATER RESOURCES AND THE INPUT-OUTPUT FRAMEWORK

Various approaches have been used to plan and assess the resilience of the water sector at regional, national, and global levels. Models built around input-output accounts have a number of advantages in this role. They are simple and transparent tools that typically form

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part of the national system of accounts and can be used to inform government and other stakeholders about the implications of various policy actions. The initial application of input-output to the interaction between the economy and the use of environment resources dates back to the 1960s and 1970s. Early models focused on constructing "fully integrated models" where both the environmental and economic systems are treated in a manner consistent with the Material Balance Principle (Daly, 1968; Isard, 1969; Miller and Blair, 2009). In this approach, flows within and between the economy and the environment operate along the same lines as interregional trade in an interregional input-output model. However, these all-encompassing economy-environment models proved difficult to operationalize.

The most popular form of environmental input-output analysis is influenced by both the Leontief (1970) generalized approach and the limited economic-ecological models (Victor, 1972). These applications recognize the one-way link between the economy and resource use but do not explicitly incorporate endogenous cleaning sectors or ecological inputs from the environment. In the present paper, we refer to this as the conventional environmental input-output approach. It uses both the regular input-output Leontief inverse and a corresponding vector of direct resource use/output ratios. This approach has been applied in a number of settings for allocating responsibility for pollution generation in single region models and the pollution embodied in trade flows, using multiregional, interregional, and international input-output frameworks (Turner et al., 2007; Wiedmann, 2009; Swales and Karen, 2017).

Subsequently, this conventional environmental input-output model has been extended and adapted to address common water concerns, producing a substantial body of literature. For instance, it has been used to consider water allocation problems in and between regions facing acute water scarcity,identifying direct and indirect consumption of scarce water resources (for example Carter and Ireri (1968), Velazquez (2006), and Guan and Hubacek (2008)). Allan (1993), on the other hand, introduces the concept of virtual water, which is the water use embedded directly or indirectly in the production of goods or services. A number of studies investigate embedded (virtual) water flows and water transfers in interregional and multiregional input-output frameworks (Dietzenbacher and Velázquez, 2007; Duchin, 2009; López-Morales and Duchin, 2013; Mubako et al., 2013; Huang et al., 2016; Bae and Dall'erba, 2018). More generally, the conventional environmental input-output method provides a framework for consumption accounting methods such as water footprints developed in a manner analogous to ecological footprints (Hoekstra and Hung, 2002). Typically, water footprints incorporate the water use outside the territorial boundaries of a region or nation required to meet the domestic public or private consumer demand of the inhabitants of that region/nation (Chapagain et al., 2006; Yu et al., 2010; Zhang et al., 2011; White et al., 2015). This is commonly addressed using interregional or multiregional input-output models. However, a number of studies take a global approach in order to include other water issues, such as waste-water, water quality, water pollution, that may pose significant threats to global water sustainability (Liu et al., 2009; Lenzen et al., 2013; Arto et al., 2016; Duchin, 2016).

An alternative approach is informed by the work of (Leontief, 1970) in which the "generalized input-output model" is discussed. This model links pollution generation directly to economic activity but also incorporates associated cleaning behaviors (Miller and Blair, 2009). The conventional matrix of (economic) input-output technical coefficients is augmented with additional rows and columns. These identify pollution generation and abate-

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ment activities by economic sectors and final demand. Leontief (1970); Allan et al. (2007b) apply this approach to pollutants whose costs are not fully internalized.[1]

In the present paper, we attempt to track the use of water that is supplied through the public water system. This is a separately identified sector in the input-output accounts and the cost - that is, the use of resources employed in the collection, preparation and movement of water - is fully internalized. This suggests an alternative way in which to identify the direct and embodied publicly-supplied water used in industrial production. Instead of using direct physical coefficients, we use the direct, indirect, and, where appropriate, induced expenditure on the water sector implied by a unit expansion in each sector. Differences between the water use multiplier values generated by the conventional environmental and the full Leontief generalized approach identify important issues for both environmental input-output analyses in particular, and also for input-output analysis as a whole. To the best of our knowledge, there is at present no attempt to apply, discuss, and explore the Leontief (1970) environmental input-output model in this way. Yet the perspectives offered provide valuable information for decision makers in the water industry.

3. METHODOLOGY

Tracking water use through the conventional environmental input-output approach, proceeds in the following way. Using the standard Leontief demand-driven model, sectorally disaggregated outputs in an economy with n sectors can be represented as (Miller and Blair, 2009):

$$\mathrm{q} = [\mathrm{I} - \mathrm{A}]^{-1}\ \mathrm{y} \tag{1}$$

In Equation (1), q and y are respectively the (n x 1) output and final demand vectors, measured in value terms, where the i^{th} element in each, respectively, is the output and final demand for the product or service generated by sector i. A is the (n x n) matrix of technical coefficients, where element, a_{ij}, is the value input of sector i directly required to produce one unit of the value output of sector j.

The $[I - A]^{-1}$ matrix is the Leontief inverse. Each element, $\alpha_{i,j}$ gives the output in sector i directly or indirectly required to produce one unit of final demand in sector j.[2] The sum of the elements of column j therefore gives the total value of output required, directly and indirectly, to meet one unit of final demand for the output of sector j. In the application of the conventional environmental input-output approach to water use, these value multipliers are transformed into physical water multipliers which measure the physical water required, directly or indirectly, to produce a unit of final demand expenditure in each sector. These are derived as the sum of the conventional column entries in the Leontief inverse, each weighted by the corresponding industry i's direct physical water coefficient. This generates a measure that is the direct and indirect use of physical water per unit value of final demand. This procedure is represented formally in Equation (2):

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[1] Leontief (1970) uses carbon monoxide and Allan et al. (2007b) uses waste as examples of pollutants generated in production.

[2] We are implicitly here constructing a Type I multiplier where household consumption is treated as exogenous. Alternative multipliers are discussed in Section 5.

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$$m_1^p = w_1 \left[I - A \right]^{-1} \tag{2}$$

In Equation (2) m_1^p is a (1x n) row vector, where the i^{th} element is the i^{th} industry's physical water multiplier value and w_1 is a (1 x n) vector where the i^{th} term is the direct physical water use in sector i, $x_{k,i}$ divided by the total output of sector i, $q_{i,T}$, so that:

$$w_{1,i} = \frac{x_{k,i}}{q_{i,T}} \qquad \forall_i \tag{3}$$

Note that here, and elsewhere in this paper, the water sector is denoted as sector k. An alternative physical water multiplier, m_2^p, can be calculated using the Leontief generalized method. In this case, rather than directly track the physical water use, the expenditure made on the water supply sector is employed to indicate the resources used in cleaning and delivering water. To identify the direct and indirect water used in meeting a unit of final demand in sector j, we locate the j^{th} element on the water supply row (the k^{th} row) of the Leontief inverse and convert this value to physical units by dividing by the average price of water.[3]

More formally, this is determined by pre-multiplying the Leontief Inverse by a (1 x n) row vector, w_2, where all elements are zero apart from the k^{th} element, which is the inverse of the average price of water, p_k^{-1}. Dividing through by the price of water converts the (1 x n) row vector of value multipliers to a vector of physical water multiplier values, m_2^p, giving (Allan et al., 2007b):

$$m_2^p = w_2 \left[I - A \right]^{-1}. \tag{4}$$

The price of water is found by summing the total expenditure on the output of the water sector, across all intermediate and final demands taken from the input-output accounts, and dividing by the total water delivered for these uses.[4] Therefore:

$$p_k = \frac{\sum_{i=1 \ldots n,f} q_{k,i}}{\sum_{i=1 \ldots n,f} x_{k,i}} = \frac{q_{k,T}}{x_{k,T}} \tag{5}$$

where the f and T subscripts stand for final and total demand, respectively. Equation (5) gives the implicit average price of water in the 2007 Welsh IO accounts. In other words, this

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[3] For example, noting the appropriate units, the conventional water multiplier for Welsh agriculture, measured in value terms, is 4.64. This means that £1,000 final demand in agriculture generates £4.64 additional demand in the water sector. If the price of water is 2.76 per cubic meter and then the corresponding physical water multiplier is 4.64/2.76 = 1.681 cubic meters of water per £1000 of final demand for agriculture. These are the figures given in Table 3 for the (unadjusted) Leontief Type I physical generalized water multiplier that applies to the Agriculture sector. This should be compared to the implied direct water coefficient from the unadjusted IO table which, for £1,000 Agricultural output equals (0.0039x1000)/2.76 = 1.41 cubic meters per £1,000 of Agricultural output.

[4] The way in which these physical figures are calculated is discussed in Section 4 and formalised in Appendix 2.

is the average price that is consistent with the estimated physical output of the water sector and the value of its output in the IO tables.[5]

The multiplier values calculated using the conventional environmental input-output approach (Equation 2) and the Leontief generalized approach (Equation 4) are the same if one central assumption of the value-denominated input-output analysis holds. This is that all uses of the output of a particular sector should face the same price for that good or service. In this specific case, this means that the two multiplier values will be equal if all users of water face the same price for water. If $m_1^P \neq m_2^P$, this is because the pattern of physical water use across sectors does not match the corresponding distribution of expenditure on the output of the water sector, as captured in the input-output accounts.[6]

Discounting data reporting errors, there are two possible reasons why the expenditure and physical use figures might not match. First, the technology for abstracting, treating, and distributing water might differ between uses. As Duchin (2016) argues, water itself is a common pool resource that is not necessarily directly paid for. In the context of input-output accounts, the water sector pays only for the resources needed to collect/abstract, treat, and distribute water but not for the water itself. The differences in price per unit of physical water delivered could therefore reflect variations in the value of inputs needed to deliver a given quantity of water to different uses.

An alternative explanation is that there is some form of price discrimination in the supply of water to different industries and elements of final demand. This perspective has been previously used by Weisz and Duchin (2006) to consider the factors surrounding the differences between physical and monetary input-output analysis in general. It has also been adopted by Allan et al. (2007b) in the specific application to the treatment of Scottish waste. Transaction and physical figures apply to the public water supply and therefore in principle go through the market mechanism. Therefore, in aggregate all the market resource costs are covered by firms and consumers paying for water for industrial or domestic use. However, if there is no difference in the resources needed to supply water to different users, then any variation between the two physical water multiplier values (m_1^P and m_2^P) is down to some form of price discrimination.

Whichever explanation applies, if these multiplier values differ, there are *prima facie* problems for input-output analysis. If the level or mix of resources needed to deliver a physical quantity of water varies across uses, and if this variation is large enough to cause significant differences in the multiplier values, then there should be greater disaggregation of the input-output table, particularly, in this case, the water sector. For example, a disaggregation between the provision of water to industrial and domestic users might be appropriate.[7] Only if the resources needed to deliver water are constant in composition across uses but

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[5] An alternative way of calculating $m_2^P = w_3[I - A]^{-1}$ where w_3 is a (1 x n) row vector where the i^{th} element is $(a_{k,i} / p_K)$.

[6] Just to be clear, to use the input-output accounts, measured in monetary values, as the basis for demand-driven analysis of any kind (not just environmental analysis) strictly requires all users of a particular sectors output to be charged the same price. Therefore, we are not in any way setting up a "straw man" in comparing the different multiplier values.

[7] In a similar situation, Allan et al. (2007a) disaggregates the electricity supply sector in the Scottish input-output table into generation and distribution and then consider different renewable technologies in the application of input-output analysis to energy issues.

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vary in their ability to deliver the same quantity of water will the conventional environmental input-output multiplier, m_1^P give the correct value (and the m_2^P value would give an inaccurate measure).

Alternatively, if price differences solely reflect price discrimination, an appropriate adjustment can be made to correct the water multiplier calculations. This involves changing the entries in the water row of the A matrix of the initial input-output accounts to reflect the true/actual water use. The initial water row vector is therefore replaced by an implied water row vector derived from multiplying the physical water use per unit of value output divided by the average price of water. The row total is then balanced by an appropriate positive or negative subsidy entry.

Again, identifying the water input as the k^{th} row, the resulting vector of multiplier values, m_3^P, is given as:

$$m_3^P = w_2[I - A^*]^{-1}y \tag{6}$$

In Equation (6), elements of the matrix A* are given as the following:

$$\begin{array}{ll} If\ i \neq k, & a_{i,j}^* = a_{i,j} \\ If\ i = k, & a_{k,j}^* = \frac{x_{k,i}p_k}{q_{i,T}} = w_{1,i}p_k \end{array} \tag{7}$$

Under price discrimination, m_3^P is the correct water multiplier value.[8] This procedure corrects the water multiplier value where price differences represent price discrimination. It is perhaps important to emphasize that this occurs through revising the entries in the conventional Leontief inverse. Imagine that there are price variations across the uses to which the output of a specific sector is put. In this case, a given expenditure is associated with a different physical output of the product, depending on the use for which that expenditure was made. This also applies to elements of final demand for water. For example, if exports receive a lower price than output sold to home consumers, then an increase in household consumption will be associated with a lower change in physical output and lower corresponding indirect and induced effects.

These problems occur whenever such price discrimination is present. Studying a relatively homogeneous sector and focusing on the physical output of that sector more easily reveals any price differences that exist. However, these challenges almost certainly apply in other sectors and could be more prevalent with greater product differentiation, though they are likely to be more difficult to detect.

Table 1 summarizes the discussion. Where the conventional vector of multiplier values, m_1^P, differ from that generated through the Leontief generalized method, m_2^P, then a fundamental assumption of input-output analysis appears to be violated. This is that the price of the physical output in water processing and delivery sector differs across various intermediate and/or final demand uses. If this is the case, the Leontief generalised method should not

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[8] An alternative way of dealing with the problem of pure price discrimination would be to construct the input-output table as a mixed table with the water sector specified in physical units (Weisz and Duchin, 2006; Duchin, 2009). However, our approach maintains the accounting identities embedded in the value denominated input-output accounts and facilitates the subsequent price adjustment calculation.

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Table 1: Multiplier Comparison and Use Table

	Environmental input-output models	Label	Formula	Data requirements
1	Conventional	m_1^p	$w_1 \left[I - A\right]^{-1}$	Physical water use data by sector
2	Leontief generalised	m_2^p	$w_2 \left[I - A\right]^{-1}$	Expenditure by sector on cleaning or delivering water and aggregate physical water use data
3	Adjusted generalised	m_3^p	$w_2 \left[I - A^*\right]^* -1$	Physical water use data by sector

be used. If the differences reflect real variation in the resources needed to clean, prepare, and deliver water to different uses, but the technology is the same for delivering to each use, then the conventional environmental multiplier is required. However, if the differences reflect price discrimination by the producers amongst users, then the adjusted generalized multipliers, m_3^P, is the most appropriate method.

Where the divergence between the relative value and quantity of water used is attributed to price discrimination, the input-output price model can determine the subsequent deviation in the prices of all commodities, and therefore the implicit price subsidies or penalties. The price model is the dual of the quantity model represented by Equation (1). In the original set of input-output accounts the sector prices are calibrated to take unit values and have the following form:

$$i = [I - A^T]^{-1} v \tag{8}$$

where i is a (n x1) vector of ones, $[I - A^T]^{-1}$ is the Leontief price multiplier and v is the vector of unit value added figures in the initial period. Equation (9) gives the corresponding set of prices, p_3^p, where the original A matrix is replaced by the augmented A* matrix.

$$p_3^p = \left[I - A^{*T}\right]^{-1} v \tag{9}$$

This is the vector of prices that would hold if all sectors and final demand uses of water were charged at the same price. Adopting the price model allows the estimation of changes in relative prices across sectors that demand water services as an intermediate input in production. Equation (10) calculates these changes, represented by Δp_3^p, as the vector of percentage price variations:

$$\Delta p_3^p = [p_3^p - i] \times 100 \tag{10}$$

If the payment for the services of the water sector were always proportional to the physical amount of water purchased, then the multiplier values generated using Equations (2), (4), and (6) would be the same, i.e. $m_1^P = m_2^P = m_3^P$ and each element of the Δp_3^p vector would be 0. However, this is not the case for the Welsh data presented in Section 4. These results are discussed in some detail in Section 5.

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4. DATA AND ADJUSTMENTS TO INPUT-OUTPUT COEFFICIENTS REQUIRED TO REFLECT ACTUAL AND IMPLIED WATER USE

This paper uses Welsh input-output accounts and data relating to the public water supply sector in Wales, a devolved region of the UK. The accounts are for 2007, the latest date for which a Welsh input-output table is available (Jones et al., 2010). These accounts identify the purchases and sales of 88 separately defined industrial sectors, one of which is water supply. Some aggregation of these sectors is required to make them consistent with the information available on the industrial use of water resources. Table A1 in the Appendix reveals the industrial aggregation used in this paper and how the 88 sectors in the Welsh input-output framework are mapped on to the 27 industries for which physical water consumption data are available.

There are two important points to note concerning the physical water data used. First, UK water figures are incomplete. There are several sources of water use and supply data, including the Department for Environment, Food, and Rural Affairs (DEFRA), the Environment Agency (EA), and the Waste and Resources Action Programme (WRAP). However, none provides the complete picture. In Wales, this partly reflects the challenge of reporting and collecting water data where catchments span political and, sometimes, water company boundaries. Secondly, there is an absence of regional natural resource data that report water use at the sectoral level and relate these to demand patterns implied by the input-output accounts. This is a specific case of the more general problem that has hindered widespread application of the Leontief (1970) environmental model to address natural resources and/or pollution concerns (Allan et al., 2007b). For analytical precision in identifying the relationship between economic activity and natural resources, water accounting data need to be collected and reported in a manner consistent with the economic accounts.

This study draws together available evidence relating to industrial and household public water use requiring the imposition of a number of study-specific assumptions. We believe that these data are useful for the experimental application of the theoretical model, presented in Leontief (1970), to the understanding of the determinants of the demand for water in Wales. Therefore, whilst the input-output data are Welsh specific, information on the physical water use has to be estimated by spatially disaggregating the combined English and Welsh Environmental Accounts. These provide information on industrial and household water use (public water supply) together with water companies' leakages in England and Wales for 2006-2007.[9] From the outset, it is important to note that this disaggregation is made primarily on the general assumption that the intensity of water use across industries and for households does not differ between England and Wales. The details of the disaggregation are given in the Appendix. Using these procedures, total Welsh public water supply in 2007 is estimated at 253 million cubic meters, of which households accounted for 158 million cubic meters (63 percent) and 69 million cubic meters (27 percent) were supplied to Welsh

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[9] Data in the UK Environmental Accounts for industrial water use in England and Wales were derived from sources including DEFRA, Environment Agency, and WRAP and include household use, water company own use and system losses. See www.ons.gov.uk/ons/dcp171778_267211.pdf. Unfortunately, more detailed water satellite accounts are not available.

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industries as intermediate inputs.[10]

Table 2 presents a condensed version of the 2007 input-output tables for Wales together with a number of additions. It shows the pattern of sales of the water sector, the physical use of water and the accounting adjustments required if expenditure on water is to match water use. Rows 1 to 6 give accounting data, measured in million GBP (British pound sterling), 2007 prices. Row 7 reports the physical water use, measured in millions of cubic meters, calculated as given in the Appendix.

Rows 1 and 2 disaggregate the expenditures on domestic output made by industrial sectors and final demand. Row 1, labelled Non-water sectors, comprises the payments made to the combined non-water sectors; that is, sectors 1-17 and 19-28 (see Table A1 in Appendix). The entries in row 2, Payments to water sector, give the payments entry for water services, sector 18, in the original input-output accounts. The total output of the water sector, at £697.82 million, comprises 0.5 percent of the total Welsh output, which in 2007 was £140,219 million. Note that actual payments for water are dominated by final demand and particularly household demand which, at £512.42 million, makes up over 73 percent of the total. The expenditure on water as an intermediate input is highest for the Chemicals and Pharmaceuticals, Public Administration, Basic Metals, and Accommodation sectors. Each of these Welsh sectors spent more than £10 million on water in 2007, the highest being Chemicals and Pharmaceuticals, at £13.29 million.

Row 3 reports the actual water use, measured in value terms, by taking the physical water use figure from row 7 and multiplying by the average price of water, as given by Equation (5). The figure in row 3 is, therefore, the expenditure for water in its different uses that would be made if water had the same price in all uses. Note that rows 2 and 3 have the same row totals, but that the entries for individual uses differ, sometimes by a very large amount. To begin, the actual use of water as an intermediate input is measured as £190.01 million, over 66 percent higher than the actual payment made for water as an intermediate. The household use indicates an equal, and opposite, position: household water payments are greater than the value of water use. For the adjusted water use by individual sectors, six sectors now have values greater than £10 million. These are, in descending order, Agriculture, Forestry and Fishing, Food and Drink, Accommodation, Health, Other Business Services, and Chemicals and Pharmaceuticals.

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[10] To be clear, this figure is the public water supply. The accuracy of these estimates is only as good as the validity of the assumptions on which they are made

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Table 2: Condensed Conventional and Full Environmental Welsh Industry by Industry Input-Output Table for 2007 (million GBP (British pound sterling))

Panel A: Industrial Sectors (1) to (14)

		Agriculture Forestry Fishing (1)	Mining and Quarry (2)	Food and Drink (3)	Clothing and Textile (4)	Wood (5)	Paper and Paper Products (6)	Printing (7)	Coke and Refined Petroleum (8)	Chemicals and Pharmaceutical (9)	Rubber and Plastic (10)	Non-Metallic Minerals (11)	Basic Metals (12)	Electronics (13)	Motor Vehicles (14)
1	Non-Water sectors	438.07	104.54	1019.2	46.88	100.63	186.26	102.38	547	574.86	291.01	166.08	1691.6	932.71	706.7
2	Water sector	5.51	0.68	6.34	0.49	0.32	0.98	0.37	4.99	13.29	1.05	1.6	10.54	3.68	1.26
3	Water Use (value)	34.09	3.15	19.48	0.48	1.56	1.08	0.29	0.84	10.84	0.7	1.65	6.27	3.33	6.3
4	Water Payment Adjustment	-28.58	-2.47	-13.14	0.01	-1.23	-0.1	0.08	4.15	2.44	0.35	-0.06	4.26	0.35	-5.04
5	Other Primary Inputs	961.53	225.03	2014.19	226.78	391.1	689.91	449.27	4583.14	2192.64	913.7	495.83	4847.32	3440.35	1746.81
6	Total Inputs	1405.09	330.26	3039.73	274.15	492.06	877.15	551.93	5135.13	2780.78	1205.76	663.51	6549.46	4376.64	2454.77
7	Physical Water Use (millM3)	12.36	1.14	7.06	0.17	0.56	0.39	0.1	0.31	3.93	0.25	0.6	2.27	1.21	2.28

Panel B: Industrial Sectors (15) to (28)

		Other Transport (15)	Furniture (16)	Electricity Gas, Waste and Sewage (17)	Water (18)	Construction (19)	Wholesale and Retail (20)	Transportation (21)	Accommodation (22)	Finance and Insurance (23)	Other Business Services (24)	Public Administration (25)	Education (26)	Health (27)	Other Services (28)
1	Non-water Sectors	535.79	192.01	2543.56	480.89	1690.98	1986.4	933.1	575.5	1154.37	1771.42	1434.4	538.05	2957.29	720.43
2	Water Sector	2.7	0.21	2.86	0.32	6.41	4.55	1.54	10.21	1.09	4.167	12.89	6.51	6.46	3.23
3	Water Use (value)	4.83	2.63	5.22	0.58	1.84	9.22	4.41	15.97	2.66	12.601	9.38	9.85	14.64	6.11
4	Water Payment Adjustment	-2.13	-2.42	-2.35	-0.26	4.57	-4.67	-2.86	-5.77	-1.57	-8.433	3.5	-3.34	-8.18	-2.88
5	Other Primary Inputs	1723.8	728.8	2734.05	216.6	3401.78	6590.29	2719.96	2039.37	2744.31	10776.2	4899.4	3107.5	5198.5	2908.28
6	Total Inputs	2262.29	921.01	5280.48	697.82	5099.17	8581.27	3654.61	2625.09	3899.78	12551.8	6346.7	3652.1	8162.2	3631.94
7	Physical Water Use (millM3)	1.75	0.95	1.89	0.21	0.67	3.34	1.6	5.79	0.96	4.57	3.4	3.57	5.31	2.21

Panel C: Other Demand Calculations

		Total Intermediate Demand	Households	Tour 1-3	Tour 4+	Tour Intl	Tour Bus	Government	Gross Fixed Capital	Stock	Exports	Exports	Total Final Demand	Total Demand Products
1	Non-water Sectors	24055.12	18731.33	217.37	964.26	296.33	217.03	13785.90	3003.90	498.60	25840.20	8828.40	72382.90	140219.10
2	Water Sector	114.26	512.42	0.14	0.63	0.17	0.15	0.00	15.44	38.56	15.23	0.84	583.56	697.82
3	Water Use (value)	190.01	436.66	0.14	0.63	0.17	0.15	0.00	15.44	38.56	15.23	0.84	507.81	697.82
4	Water Payment Adjustment	-75.76	75.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	75.76	0.00
5	Other Primary Inputs	273.40	17639.60	26.20	159.50	41.90	28.20	481.70	2413.10	189.30	5448.10	1382.20	27809.81	100776.20
6	Total inputs	-33.90	36883.40	243.70	1124.40	338.40	245.40	14267.60	5432.40	726.50	31303.50	10211.10	100776.20	198278.90
7	Physical Water Use (millM3)	68.87	158.27	0.05	0.23	0.06	0.05	0.00	5.59	13.98	5.52	0.31	184.05	252.92

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The figures in row 4, Additional payment for water, are the differences between the unadjusted (row 2) and adjusted (row 3) water payment entries. The row total is zero, so that overpayments are just balanced by underpayments. Where the entries are positive in this row, it implies an overpayment for water. This occurs for household consumption and industrial sectors such as Coke and Refined Petroleum, Chemicals and Pharmaceuticals, Basic Metals, Construction, and Public Administration. Some sectors, such as Chemicals and Pharmaceuticals and Basic Metals, were identified in a previous study as high users of water per GBP of Welsh GVA (Gross Value Added) (Jones et al., 2010).[11]

A negative Row 4 entry shows that in the unadjusted system these sectors are net under-payers. Of the 28 industrial sectors, 19 sectors are net under-payers with Agriculture, Forestry and Fishing, Food and Drink, Education, and Health responsible for over three quarters of this underpayment.

In Table 2, rows 5 and 6 give the other primary inputs and total (unadjusted) value of inputs figures for each sector from the original Welsh table. The other primary inputs include payments for labor and other value added, together with imports (from both the rest of the UK and the rest of the World), taxes and subsidies. For each sector, the unadjusted value of inputs figure is also the value of output figure.

If the difference in the cost of water for various uses solely reflects price discrimination, then the negative or positive row 4 entries indicate whether any given sector is directly subsidizing water use in other parts of the economy or is being subsidized. In addition to looking at the relative expenditure by individual production sectors, it is also important to identify the position relative to final demand uses. There are limitations here, because for all non-household final demand sectors the assumption has been imposed, in the face of insufficient physical water use data, that these sectors fully pay for the water that they use, hence their zero value in row 4. However, the household sector's additional payment entry, which is based on actual data, has a high positive value £75.76 million suggesting that households pay much more for water than their physical water use implies and are subsidizing industrial water use, taken as a whole.

5. APPLICATION TO ANALYSIS OF INDUSTRIAL WATER USE IN WALES

In this section we use the Welsh data outlined in Section 4 to calculate the water multiplier m_1^P, m_2^P, m_3^P given by Equations (2), (4), and (6) in Section 3. We also use Equations (8), (9), and (10) to measure the price impacts from imposing uniform pricing for Welsh water.

5.1. Physical Water Multiplier Values

Table 3 presents the Type I and Type II values for the three physical water multipliers $(m_1^P, m^P_{,} m_3^P)$ outlined in Section 3. Also reported are the direct water coefficients required to calculate these multipliers. Differences exist between Type I and Type II multipliers (Miller and Blair, 2009; Emonts-Holley et al., 2015). Type I multipliers include only direct and

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[11] Jones et al. (2010) also employed Welsh input-output tables for 2007, but used a different set of water consumption data.

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indirect effects. In measuring Type I multipliers, household consumption is held constant and only endogenous intermediate water demands are included as elements of the supply chain. Type I multipliers are typically used for footprint analysis. Type II multipliers incorporate the induced water consumption of direct workers and also those workers attributed to the sector's extended supply chain. This would be the most appropriate multiplier value for increases in activity that were expected to be accompanied by increases in population in the relevant spatial area.[12]

The first data column gives the physical water use coefficient ($x_{k,i}/q_{i,T}$), measured in thousands of cubic meters per million GBP of output. These figures comprise the elements of the vector, w_1. On this measure, the four most water intensive sectors, in descending order, are Agriculture, Forestry, and Fishing, Mining and Quarrying, Food and Drink, and Accommodation. All of these sectors have a water intensity value over 2,000 cubic meters of water per million GBP of output. The Agriculture, Forestry, and Fishing value at 8,794 cubic meters is particularly high.

The second data column reports the corresponding original direct water coefficient in the A matrix. These figures give the proportion of total costs in that sector going directly to the water sector. Using this metric, the top four most water intensive sectors in Wales are: Chemicals and Pharmaceuticals, Agriculture, Forestry, and Fishing, Accommodation, and Non-Metallic Minerals. It is clear that ordering the sectors by the share of costs which go to intermediate water expenditure differs from ordering by the physical water-use intensity. The third column gives the adjusted expenditure coefficients calculated by multiplying the physical coefficients in column 1 by the price of water calculated using Equation (5) and dividing by one thousand. These are the water row coefficients used in the adjusted, A*, matrix incorporated in the Leontief inverse employed in the calculation of m_3^P. Given that the figures in column 3 are a scalar multiple of those in column 1, the ordering of water intensities is exactly the same in columns 1 and 3. However, a comparison of columns 2 and 3 indicates the extent to which the two water intensity measures differ.

For most industries, the adjusted coefficient in column 3 is greater than the coefficient in the original/conventional Leontief input-output table shown in column 2. However, there are nine sectors where the conventional input-output coefficients are higher than their adjusted counterparts. The biggest differences are in the Chemical and Pharmaceuticals, Public Administration, and Clothing and Textile sectors. Linking these findings to the results in Table 2, in all these sectors, the actual payment is higher than the value of the water used, based on the price determined in Equation (5). In twenty sectors where the Leontief water coefficients are higher than that of conventional input-output tables, the bigger differences are in Agriculture, Forestry, and Fishing, Mining and Quarrying, Food and Drink, and Furniture sectors. From the results in Table 2, these sectors' payments for water are lower than the amount of water they consumed, valued at the constant price across all uses determined by Equation (5).

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[12] There are different variants of the Type II multiplier (Emonts-Holley et al., 2015). In this paper we use the Miller and Blair (2009) formula.

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Table 3: Water Use Coefficients and Multipliers in Wales Using Different Input-Output Methods

	Sector/Activity	Conventional environmental coefficients	Leontief coefficients	Adjusted coefficients	Conventional environmental multipliers		Leontief generalized multipliers		Augmented Leontief multipliers	
					$m_1^P = w_1[I-A]^{-1}y$		$m_2^P = w_2[I-A]^{-1}y$		$m_3^P = w_2[I-A^*]^{-1}y$	
		$X_k, i/q_i, T$	a_k, i	$X_k, ip/q_i, T$	Type I	Type II	Type I	Type II	Type I	Type II
1	Agriculture, Forestry & Fishing	8.794	0.00392	0.02426	9.791	13.461	1.681	5.732	9.806	13.526
2	Mining & Quarrying	3.458	0.00206	0.00954	3.789	6.312	0.897	3.682	3.794	6.334
3	Food & Drink	2.323	0.00209	0.00641	3.748	6.289	1.073	3.878	3.753	6.31
4	Clothing & Textile	0.631	0.00179	0.00174	0.751	3.827	0.718	4.113	0.751	3.824
5	Wood	1.146	0.00066	0.00316	1.682	3.984	0.366	2.907	1.685	3.993
6	Paper & Paper Products	0.447	0.00112	0.00123	0.624	2.536	0.499	2.609	0.624	2.535
7	Printing	0.189	0.00067	0.00052	0.297	3.492	0.307	3.835	0.297	3.49
8	Coke & Refined Petroleum	0.06	0.00097	0.00016	0.127	1.081	0.395	1.448	0.126	1.078
9	Chemicals and Pharmaceuticals	1.413	0.00478	0.0039	1.574	3.767	1.832	4.253	1.574	3.763
10	Rubber and plastic	0.211	0.00087	0.00058	0.358	3.463	0.424	3.852	0.358	3.46
11	Non-Metallic Mineral	0.903	0.00241	0.00249	1.12	4.009	0.998	4.187	1.12	4.007
12	Basic Metals	0.347	0.00161	0.00096	0.507	2.973	0.698	3.42	0.507	2.97
13	Electronics & Electrical Engineering	0.276	0.00084	0.00076	0.401	3.000	0.391	3.26	0.401	2.998
14	Motor Vehicles	0.93	0.00051	0.00257	1.115	3.222	0.323	2.649	1.116	3.227
15	Other Transport	0.773	0.00119	0.00213	0.925	3.405	0.531	3.27	0.925	3.406
16	Furniture	1.036	0.00023	0.00286	1.238	3.78	0.153	2.958	1.24	3.787
17	Electricity, Gas, Waste & Sewage	0.358	0.00054	0.00099	0.747	3.018	0.391	2.898	0.748	3.019
18	Water	0.303	0.00046	0.00084	362.448	362.451	362.81	362.451	362.811	362.813
19	Construction	0.131	0.00126	0.00036	0.323	3.668	0.635	4.328	0.322	3.663
20	Wholesale & Retail	0.389	0.00053	0.00107	0.574	4.437	0.278	4.542	0.574	4.436
21	Transportation	0.437	0.00042	0.00121	0.585	4.67	0.232	4.742	0.585	4.67
22	Accommodation	2.205	0.00389	0.00608	2.661	6.737	1.552	6.052	2.663	6.743
23	Finance & Insurance	0.247	0.00028	0.00068	0.419	3.738	0.193	3.857	0.419	3.737
24	Other Business Services	0.364	0.00033	0.00100	0.439	2.9	0.172	2.888	0.44	2.9
25	Public Administration	0.536	0.00203	0.00148	0.683	5.679	0.834	6.349	0.683	5.673
26	Education	0.978	0.00178	0.00270	1.110	8.233	0.719	8.583	1.111	8.23
27	Health	0.65	0.00079	0.00179	0.995	5.302	0.458	5.213	0.996	5.303
28	Other Services	0.61	0.00089	0.00168	0.749	5.04	0.398	5.135	0.749	5.039

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The figures in columns 4 and 5 report the physical water Type I and Type II multiplier values using the conventional environmental input-output approach. For the Type I multiplier this is m_1^P as given in Equation (2), whereas the Type II multiplier formulation is given in the Appendix. These multiplier values are measured in thousand cubic meters for each million GBP of final demand expenditure.

The conventional Type I physical water multiplier value presented in column 4 must be higher than the corresponding direct water coefficient shown in column 1, because it incorporates both the direct water input and the embedded water in the other intermediate inputs. For example, in Agriculture, Forestry, and Fishing, the direct water use is 8,794 cubic meters per million GBP final demand, whereas the conventional Type I value is 9,791 cubic meters. Typically, the difference is relatively small, but in some cases the proportionate differences can be large. The Food and Drink sector has a direct water coefficient of 2,323 cubic meters but a Type I multiplier value that is 60 percent higher at 3,748 cubic meters per million GBP of final demand.

The conventional physical Type II water multiplier values are higher still, as they include additional induced household water use. The Type II measure used endogenizes all the household water use, which is more than double intermediate water use. Therefore, the Type II physical water multiplier is significantly higher than the Type I value for most sectors. Although the Agriculture, Forestry, and Fishing sector maintains its position as the most water intensive on this measure, other more labor intensive sectors begin to play a more prominent role. Education moves from 1,110 cubic meters on the Type I multiplier to around 8,233 cubic meters for the Type II and takes second place on that measure. Accommodation shows a similarly large gain moving from the Type I to Type II multiplier measure and at around 6,737 cubic meters per million GBP final demand is the third most water intensive sector.[13]

The Type I and Type II physical water multiplier values, calculated on the basis of water sector payments, are shown in columns 6 and 7. Note the low values for the Type I multipliers. For 20 industries, the Type I m_2^p multiplier value is lower than the corresponding m_1^p figure. The Type I m_2^p multiplier value is never greater than 2,000 cubic meters per million GBP and in only five sectors is it greater than 1,000 cubic meters per million GBP. Chemicals and Pharmaceuticals has the largest value, at around 1,832 cubic meters, followed by the Agriculture, Forestry, and Fishing, Accommodation, and Food and Drink sectors. The relatively low measure stems from lower expenditures on water as an intermediate input than would be expected from physical water use.

The Type II values incorporate household water use that is overvalued in the expenditure (as against physical) figures. This means that there is no overall bias in the Type II m_2^p value, but there are big differences in the Type II values for some individual sectors such as Agriculture, Forestry, and Fishing, Mining and Quarrying, Food and Drink, and Wood Products.

The m_3^p multiplier adjusts the Leontief inverse so that the technical water expenditure coefficients match the physical intermediate and final demand water use values. If the adjusted

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[13] Discounting the water sector itself, of the remaining 27 sectors only 3 have a Type II conventional Type II multiplier less than double the Type I value.

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A matrix is used, the conventional and extended Leontief multiplier values are brought into line, so that $w_1[I-A]^{-1} = w_2[I-A]^{-1}$. This is the appropriate procedure if the mismatch between the physical and expenditure water use data is solely due to price discrimination amongst water uses. In this case, it is clear that the m_3^p values are much closer to those for m_1^p than to those for m_2^p. This suggests that calculating the physical water multipliers by just tracking the value of output of water sector may potentially give very inaccurate multiplier values for some sectors. On the other hand, the conventional environmental approach, which augments the value of the Leontief inverse with direct physical water/output ratios, generates multiplier estimates which, whilst theoretically incorrect, are extremely close to the m_3^p values. This almost certainly reflects the small scale of the water sector in the Welsh economy. However, the water sector multipliers are very high compared to those in other sectors. This is because it contains the direct effects while other sectors contain only indirect effects. Adjusting the coefficients for a large sector should have bigger impacts on the calculated inverse values.

5.2. Price Multiplier

If the variation across uses in the price paid per unit of delivered physical water is the result of pure price discrimination, then the impact on commodity prices of adjusting the water payments for actual direct water use can be calculated using Equations (8), (9), and (10). The deviations from the original prices are given in Table 4. These figures show whether or not sectors at present bear the full resource cost of water use through direct and/or knock on impacts on the price of their output. Column 1 reports the impacts on the prices of sectoral output using the Type I price multiplier values and the adjusted system. In this case wage payments are taken as an element of the value added vector, v, and do not adjust to variations in the sector prices; the nominal wage is held constant. The percentage changes in prices reported in column 2 identify the corresponding results using Type II multipliers. Essentially this holds the real wage constant and adjusts the nominal wage to changes in sector prices. An important issue here is that the price consumers pay for water is above the average price so that an adjustment to uniform pricing will have a direct impact on the nominal wage.

In the Type I case, there are seven sectors where the price of output would be lower if a uniform price is charged for water across all uses. The largest negative adjustments are for the Construction, Coke and Refined Petroleum, and Chemicals and Pharmaceuticals sectors. However, these impacts are small. These sectors all suffer a cost disadvantage of less than 0.1 percent stemming from the existing water price differentials. In 21 sectors the adjustment increases the Type I price multiplier values. In some cases, the impact is particularly high, with the Agriculture, Forestry, and Fishing price increasing by 2.24 percent and prices in the Mining and Quarrying, and Food and Drink sectors rising by 0.80 percent and 0.74 percent, respectively.

In calculating the Type II adjusted prices, two changes to the Type I method are made. First, wage income is removed from the vector of sectoral value added, so that all elements in the value added vector are reduced. Second, the A matrix is augmented to incorporate wage and household expenditures. The net impact is to reduce the adjusted price in all sectors

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Table 4: Impact on Output Price of the Adjustment to Full Leontief Environmental Input-Output Accounts

		Percentage change in price multiplier relative to unadjusted price input-output	
	Sector/Activity	Type I (%)	Type II (%)
1	Agriculture, Forestry and Fishing	2.24	2.18
2	Mining and Quarrying	0.80	0.76
3	Food and Drink	0.74	0.70
4	Clothing and Textiles	0.01	-0.04
5	Wood	0.36	0.33
6	Paper and Paper Products	0.04	0.00
7	Printing	0.00	-0.06
8	Coke and Refined Petroleum	-0.07	-0.09
9	Chemicals and Pharmaceuticals	-0.07	-0.11
10	Rubber and Plastic	-0.02	-0.07
11	Non-metallic Mineral	0.03	-0.02
12	Basic Metals	-0.05	-0.09
13	Electronics and Electrical Engineering	0.00	-0.04
14	Motor Vehicles	0.22	0.18
15	Other Transport	0.11	0.07
16	Furniture	0.30	0.26
17	Electricity, Gas,Waste and Sewage	0.10	0.06
18	Water	0.08	0.04
19	Construction	-0.09	-0.14
20	Wholesale and Retail	0.08	0.02
21	Transportation	0.10	0.03
22	Accommodation	0.31	0.24
23	Finance and Insurance	0.06	0.01
24	Other Business Services	0.07	0.03
25	Public Administration	-0.04	-0.13
26	Education	0.11	-0.01
27	Health	0.15	0.08
28	Other Services	0.10	0.03

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against the Type I value. This means that if with the Type I multiplier the price adjustment is negative, it is even more negative with the Type II calculation. On the other hand, if the Type I price change is positive, the Type II value will be smaller and could even be negative.

The biggest difference occurs with the Education sector. Row 4 in Table 2 shows that the Education sector is a net under-payer for water. This is reflected in the higher Type I price multiplier in the first column of Table 3. However, the Education sector is a labor/wage intensive sector. This means that, in the Type II case, it is impacted by the effect of households over-paying for water as an "input" to the provision of labor services. In the Type II price multiplier, the Education sector becomes a net over-payer for water.

6. CONCLUSION

This paper explores alternative input-output approaches to generating physical multiplier values that may be used to understand water resource use and supply in Wales. In particular, it compares the results from using the conventional physical environmental input-output model with an approach based upon an earlier generalized Leontief (1970) method, both with and without adjustments to the A matrix. Essentially, the generalized Leontief method uses the demand for the output of the industry involved in the collection, preparation and movement of water as an index of physical water use. The motivation for using this alternative approach came from the importance attached in Leontief (1970) for cleaning sectors. However, in many other cases the physical use of environmental goods such as rare metals, could be tracked by the expenditures of the industries supplying such goods.

In the case of Wales, we find that the price paid per physical amount of water appears to vary greatly among different uses. In general, the data suggest that water used for household consumption is charged at a higher price than for intermediate industrial demand. There is also wide price variation across different industries. Only if physical water-use data are employed to adjust the input-output A matrix does the generalized Leontief model work satisfactorily. In principle, this is problematic for input-output analysis in general. However, the small scale of the Welsh water sector means that in this case the conventional environmental input-output multipliers appear to be quite accurate.

Our recommendation is that the adjusted environmental generalized input-output model should be employed in water management and planning as this model incorporates the resource costs of taking water resources from the environment to meet economic needs. We believe this aspect of the approach is particularly valuable as water companies and regulators across UK regions have to focus far more on the opportunity costs associated with public water supply in an ecosystems services framework which highlights the different services that water bodies provide. Indeed, these perspectives are particularly important in the case region considered, Wales.

Here, issues around water demand and supply are complex. Currently, the debate focuses on household affordability of water (and sewage), the need for integrated water catchment management in the region, and how to frame competing demands for the resource. The latter is not just in terms of demand from industry and households, but also competing demands to maintain the ecosystem services provided by water bodies. In turn, the regional

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government takes the improvement and maintenance of these environmental services very seriously in the context of a legal sustainable development duty tied into the Wellbeing of Future Generations (Wales) Act 2015 (Natural Resources Wales, 2016). Consequently, there is a need for far better intelligence on how water demands adjust, both directly and indirectly, in response to industry change in the region. Moreover, there are pressures to show how changes in demand in an industry in a water catchment might rebound in terms of increases in elements of the regional supply chain placed in other water catchments. This is accepted as a fundamental component of better integrated water basin management.

In terms of implications for policy, the key issue is that accurate physical water multiplier values are required in order to calculate the impact of industrial development strategies on the demand for water and therefore the sustainability of growth. The major policy implication of this work is that water expenditure information reported in the core economic input-output accounts could be inadequate for producing accurate physical water multiplier values. This implies that the tables must be augmented with direct physical water coefficients. However, physical data on resource use and supply (often referred to as environmental satellite accounts) are commonly not collected and published. The paucity in data collection means that decisions and perspectives developed on the basis of the information commonly reported in input-output tables might not be suitable to examine how changes in the structure of the economy have consequences for direct, indirect and induced water use.

REFERENCES

Allan, G, P G McGregor, J K Swales, and K Turner. (2007a) “Impact of Alternative Electricity Generation Technologies on the Scottish Economy: An Illustrative Input-output Analysis,” *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(2), 243–254.

Allan, Grant J, Nicholas D Hanley, Peter G Mcgregor, J Kim Swales, and Karen R Turner. (2007b) “Augmenting the Input–output Framework for Common Pool Resources: Operationalising the Full Leontief Environmental Model,” *Economic Systems Research*, 19(1), 1–22.

Allan, J A. (1993) *Proceedings of the Conference on Priorities for Water Resources Allocation and Management*, 13, 26.

Arto, Inaki, Valeria Andreoni, and Jose Manuel Rueda-Cantuche. (2016) “Global Use of Water Resources: A Multiregional Analysis of Water Use, Water Footprint and Water Trade Balance,” *Water Resources and Economics*, 15, 1–14.

Bae, Jinwon and Sandy Dall’erba. (2018) “Crop Production, Export of Virtual Water and Water-saving Strategies in Arizona,” *Ecological Economics*, 146, 148–156.

Carter, Harold O and Dunstan Ireri. (1968) *Linkage of California-Arizona Input-output Models to Analyze Water Transfer Patterns.* University of California, Department of Agricultural Economics.

Chapagain, Ashok Kumar, Arjen Ysbert Hoekstra, Hubert H G Savenije, and Resham Gautam. (2006) “The Water Footprint of Cotton Consumption: An Assessment of the Impact of Worldwide Consumption of Cotton Products on the Water Resources in the Cotton Producing Countries,” *Ecological economics*, 60(1), 186–203.

©Southern Regional Science Association 2019.

Daly, Herman E. (1968) "On Economics as a Life Science," *The Journal of Political Economy*, 76(3), 392–406.

DEFRA. (2016). "National Policy Statement for Water Resources," Department for Environment, Food, and Rural Affairs: United Kingdom. Available online in May 2019 at https://consult.defra.gov.uk/water/nps-water-supply-planning-act-2008/supporting_documents/Consultation document for National Policy Statement for Water Resources.pdf.

Dietzenbacher, Erik and Esther Velázquez. (2007) "Analysing Andalusian Virtual Water Trade in an Input–output Framework," *Regional Studies*, 41(2), 185–196.

Duchin, Faye. (2009) "Input-output Economics and Material Flows," In *Handbook of Input-output Economics in Industrial Ecology.* Springer: pp. 23–41.

Duchin, Faye. (2016) "A Global Case-Study Framework Applied to Water Supply and Sanitation," *Journal of Industrial Ecology*, 20(3), 387–395.

Emonts-Holley, Tobias, Andrew Ross, and J Kim Swales. (2015) *Type II Errors in IO Multipliers.* University of Strathclyde.

Guan, Dabo and Klaus Hubacek. (2008) "A New and Integrated Hydro-economic Accounting and Analytical Framework for Water Resources: A Case Study for North China," *Journal of Environmental Management*, 88(4), 1300–1313.

Hoekstra, Arjen Y and Pin Q Hung. (2002) "Virtual Water Trade," *A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. Value of Water Research Report Series*, 11, 166.

Huang, Yue, Yalin Lei, and Sanmang Wu. (2016) "Virtual Water Embodied in the Export from Various Provinces of China using Multi-regional Input–output Analysis," *Water Policy*, p. wp2016002.

Isard, Walter. (1969) "Some Notes on the Linkage of the Ecologic and Economic Systems," *Papers in Regional Science*, 22(1), 85–96.

Jones, Calvin, Jane Bryan, Max Munday, and Roberts Annette. (2010). "Input-Output Tables for Wales 2007," Welsh Economy Research Unit, Cardiff Business School: Cardiff, UK.

Lenzen, Manfred, Daniel Moran, Keiichiro Kanemoto, and Arne Geschke. (2013) "Building Eora: A Global Multi-region Input–output Database at High Country and Sector Resolution," *Economic Systems Research*, 25(1), 20–49.

Leontief, Wassily. (1970) "Environmental Repercussions and the Economic Structure: An Input-output Approach," *The Review of Economics and Statistics*, pp. 262–271.

Liu, Junguo, Alexander J B Zehnder, and Hong Yang. (2009) "Global Consumptive Water use for Crop Production: The Importance of Green Water and Virtual Water," *Water Resources Research*, 45(5).

López-Morales, C and F Duchin. (2013) "Achieving Water Sustainability: Analyzing Scenarios Restricting Water Withdrawals from Surface and Underground Sources with an Inter-regional Model of the Mexican Economy," *Environmental Science Technology.*

Miller, R.E and P.D Blair. (2009) *Input-Output Analysis Foundations and Extensions.* Cambridge University Press, Cambridge, United Kingdom.

Mubako, Stanley, Sajal Lahiri, and Christopher Lant. (2013) "Input–output Analysis of Virtual Water Transfers: Case Study of California and Illinois," *Ecological Economics*, 93, 230–238.

Natural Resources Wales. (2016). "The State of Natural Resources Report (SoNaRR): Assessment of the Sustainable Management of Natural Resources," Natural Resources Wales: Wales, UK. Available online in June 2019 at https://naturalresources.wales/media/682045/chapter-5-wellbeing-final-for-publication.pdf.

Swales, J. Kim and Turner Karen. (2017) "Environmental Economics," In *Handbook of Input–Output Analysis*. Cheltenham: Edward Elgar Publishing: pp. 329–354.

Turner, Karen, Manfred Lenzen, Thomas Wiedmann, and John Barrett. (2007) "Examining the Global Environmental Impact of Regional Consumption Activities Part 1: A Technical Note on Combining Inputoutput and Ecological Footprint Analysis," *Ecological Economics*, 62(1), 37–44.

Velazquez, Esther. (2006) "An Input–output Model of Water Consumption: Analysing Intersectoral Water Relationships in Andalusia," *Ecological Economics*, 56(2), 226–240.

Victor, Peter A. (1972) *Economics of Pollution.* Macmillan International Higher Education.

Weisz, Helga and Faye Duchin. (2006) "Physical and Monetary Inputoutput Analysis: What Makes the Difference?," *Ecological Economics*, 57(3), 534–541.

Welsh Government. (2016). "The Welsh Government Guiding Principles for Developing Water Resources Management Plans (WRMP's) for 2020," Welsh Government: Welsh, UK. Available online in June 2019 at https://gov.wales/docs/desh/publications/160405-guiding-principles-for-developing-water-resources-management-plans-for-2020-en.PDF.

White, David J, Kuishuang Feng, Laixiang Sun, and Klaus Hubacek. (2015) "A Hydro-economic MRIO Analysis of the Haihe River Basin's Water Footprint and Water Stress," *Ecological modelling*, 318, 157–167.

Wiedmann, Thomas. (2009) "A Review of Recent Multi-region Inputoutput Models used for Consumption-based Emission and Resource Accounting," *Ecological Economics*, 69(2), 211–222.

Yu, Yang, Klaus Hubacek, Kuishuang Feng, and Dabo Guan. (2010) "Assessing Regional and Global Water Footprints for the UK," *Ecological Economics*, 69(5), 1140–1147.

Zhang, Zhuoying, Hong Yang, and Minjun Shi. (2011) "Analyses of Water Footprint of Beijing in an Interregional Inputoutput Framework," *Ecological Economics*, 70(12), 2494–2502.

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A. APPENDIX

A.1. Sectoral Aggregation in the Welsh Input Output Account

Table A1: Production Sectors/Activities Identified in the Welsh Input-Output Tables, 2007

	Sectors	SIC 2007 code	Input-Output 2007 groups
1	Agriculture, Forestry and Fishing	A	1,2
2	Mining and Quarrying	B	3,4
3	Food and Drink	C10/11/12	5,6,7,8,9,10,11
4	Clothing and Textiles	C13,C14,C15	12,13
5	Wood	C16	14
6	Paper and Paper Products	C17	15
7	Printing	C18	16
8	Coke and Refined Petroleum	C19	17
9	Chemicals and Pharmaceutical	C20/C21	18,19,20
10	Rubber and Plastic	C22	21,22
11	Non-metallic Mineral	C23	23,24
12	Basic Metals	C24/C25	25,26,27,28
13	Electronics and Electrical Engineering	C26/C27/C28/C32/C33	29-37,41
14	Motor Vehicles	C29	38
15	Other Transport	C30	39
16	Furniture	C31	40
17	Electricity, Gas, Waste and Sewerage	D	42,43,44,45,46,47,48,87
18	Water	E	49
19	Construction	F	50
20	Wholesale Retail	G	51,52,53
21	Transportation	H	60-63
22	Accommodation	I	54-59
23	Finance and Insurance	K	67,68,69
24	Other Business Services	LMN	70,71,72,73-79
25	Public Administration	O	80
26	Education	P	81
27	Health	Q	82
28	Other Services	JRSTU	65,66,83-86, 88

A.2. Estimating Welsh Water Use

The vector of Welsh industrial water use is calculated in the following way. Each element is determined by dividing the England and Wales water use figure in each industry in proportion to the corresponding industry's employment levels in the two regions, shown as:

$$x_{k,i}^{W} = x_{k,i}^{E+W}\left[\frac{e_i^{W}}{e_i^{E+W}}\right] \tag{A.1}$$

.

In this equation, e_i is employment in industry i, and the W and E superscripts apply to Wales and England respectively.

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The Welsh household physical water use, $x_{k,h}^{W}$, is estimated based on the Welsh share of the England and Wales population (Pop^{W}/Pop^{E+W}) so that:

$$x_{k,h}^{W} = x_{k,h}^{E+W}\left[\frac{Pop^{W}}{Pop^{E+W}}\right]. \tag{A.2}$$

However, there is limited information on physical water supplied to all non-household final demand uses, $x_{k,nh}^{W}$. This is essentially demand for Welsh water exported to England. The assumption is made that the physical share of non-household water output to the physical total output is equal to the value share of non-household final demand to the value of all Welsh water output, as given in the Welsh input-output tables. This corresponds to the assumption that all non-household final demand uses pay the industry average price for the water that they purchase as determined in Equation 5 of the text. This implies that:

$$x_{k,nh}^{W} = \left[\frac{q_{k,nh}^{W}}{q_{k,T}^{W} - q_{k,nh}^{W}}\right]\left[x_{k,h}^{W} + \sum_{i} x_{k,i}^{W}\right] = \frac{q_{k,nh}^{W}}{p_k} \tag{A.3}$$

$$x_{k,T}^{W} = \sum_{i} x_{k,i}^{W} + x_{k,h}^{W} + x_{k,nh}^{W}. \tag{A.4}$$

Using these assumptions, Welsh water production in 2007 (public water supply) equals 253 million cubic meters. Households accounted for 158 million cubic meters (63 percent) and industry 69 million cubic meters (27 percent).

A.3. Type II Multipliers

The basic equation for the Miller and Blair Type II multiplier is given by Equation (A5) which corresponds to Equation 1 for the Type I multiplier.

$$\begin{bmatrix} I-A & -h \\ -a_w & I \end{bmatrix}^{-1}\begin{bmatrix} y_N \\ 0 \end{bmatrix} = \begin{bmatrix} q \\ W \end{bmatrix} \tag{A.5}$$

In Equation (A5), y_N is the (nx1) vector of final demands, in this case not including household consumption. The entry a_w is a (nx1) row vector of wage coefficients, where the jth element $a_{w,j}$ is the wage payment in sector j divided by the total output of that sector. The vector h is a (nx1) column vector of household consumption expenditure coefficients. In the Miller and Blair case, the jth element of this household consumption vector, $h_j = \frac{y_{H,j}}{W}$, where $y_{H,j}$ is the jth element of the household final demand vector in the IO accounts and W is the total wage payments in the base year. $\begin{bmatrix} 1-A & -h \\ -a_w & 1 \end{bmatrix}^{-1}$ is the Type II Miller and Blair Leontief inverse. If the elements of this inverse are identified as $\beta_{i,j}$, then the Miller and Blair Type II output multiplier for industry j, m_j^{II}, is given as:

$$m_j^{II} = \sum_{i=1}^{n} \beta_{i,j} \tag{A.6}$$

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For any sector, j, the Type II multiplier is the sum of the first n entries in the jth column of the Type II Leontief inverse. The $(\mathrm{n}+1)^{\mathrm{th}}$ entry in each column is the direct, indirect and induced wage income generated by one unit of final demand for the output of that sector and is therefore excluded from the multiplier value.

The corresponding Type II physical water multipliers correspond to the Type I multipliers defined in Equations 2, 3, and 6. This means that for the conventional physical Type II multiplier for commodity j, $m_{1,j}^{p,II}$, the β vector is constructed using the conventional A matrix and each element is weighted by the corresponding element of the vector w_1. For the Leontief generalized physical Type II multiplier, $m_{2,j}^{p,II}$, the β vector is constructed using the conventional A matrix, but each element is weighted by the corresponding element of the vector w_2. Finally for the adjusted generalised physical Type II multiplier the elements of the β vector are constructed using the appropriate A^* matrix and each element is again weighted by the corresponding element of the w_2 vector.

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