The concept of 'virtual water' — a critical review

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Executive summary

Virtual (or embodied) water is a measure of the total water used in production of a good or service.

The concept was initially used to illustrate the advantages to water scarce nations of trade with other nations, rather than attempting to produce all goods locally.

In recent times the concept has been applied to argue against production of commodities with high embodied water content, or to argue against their export on the basis that these activities waste scarce water resources. Virtual water estimates have also been used as an indicator of environmental damage of certain production activities.

This note examines the methodology for estimating virtual water and identifies several important flaws in the virtual water concept. These flaws render the virtual water concept meaningless and casts serious doubts on the wisdom of applying the concept of virtual water to draw conclusions regarding the desirability or otherwise of alternative production activities.

Key shortcomings of 'virtual water' measures are that the concept:

1. Relies on an assumption that all sources of water, whether in the form of rainfall or provided through an irrigation system, are of equal value.
2. Implicitly assumes that water that would be released by reducing a high water use activity would necessarily be available for use in a less water-intensive activity. For example, the implicit assumption is that water used in rangeland beef production would be available to be used to produce an alternative, less water-intensive activity. As a practical matter this may not be the case, nor might the alternatives be economic.
3. Fails as an indicator of environmental harm nor does it provide any indication of whether water resources are being used within sustainable extraction limits. The use of virtual water estimates therefore offer no guidance for policy makers seeking to ensure that environmental objectives are being met.

The deficiencies with the concept of virtual water mean that there is a significant risk in relying on these measures to guide policy conclusions, such as proposals to restrict the production and/or export of commodities that have high 'virtual water' content. Especially burdensome on business, and of no benefit in the pursuit of environmental policy, would be proposals for the development of virtual water labelling standards on food.

1 Introduction

As the widespread drought continues and pressures on Victorian (and more generally, Australian) water resources increase, increasing attention is being given to how much water is used by primary industries in Victoria and for what purpose.

In discourse on water resource management policy, the concept of 'virtual water' has gained prominence as a tool to illustrate the relationship between water inputs and industry outputs. In turn, this concept is being used to draw broader public policy insights. In Victoria, for example, current research is being funded by the Victorian Water Trust into the 'Virtual Water Cycle' for Victoria.

However, there appears to be limited understanding of the economics of this partial input-output measure which may lead to spurious conclusions regarding the relative efficiency, or desirability, of alternative production systems — and may prompt inappropriate policy responses.

Frontier Economics in association with Dr Alistair Watson has been commissioned by the Victorian Department of Primary Industries (DPI) to review and assess the concept and application of virtual water in policy making

The report is structured as follows:

- Section 2 defines the concept of 'virtual water', its origins, its calculation and how it is used;
- Section 3 develops an economic framework to aid understanding of the concept of virtual water;
- Section 4 assesses the extent to which the concept and application of virtual water can contribute to sound economic and public policy; and
- Section 5 draws together our key conclusions.

2 What is 'virtual water'?

2.1 THE CONCEPT OF 'VIRTUAL WATER'

'Virtual water' is a measure of the total water used in producing a good or service. For example, is has been estimated that to produce one kilogram of wheat requires about 1000 litres of water.

The total amount of water required to produce a particular quantity of output will depend critically on the prevailing production conditions, including place and time of production and water use efficiency (Hoekstra 2003). Virtual water is also referred to as 'embedded water' because it represents the water used in the whole production chain embedded in end-products (rather than the actual water content of the finished product).

Virtual water can be calculated in principle for any good (including both agricultural and industrial) or service. The calculation takes into account water from all sources that is directly used in production, as well as incorporating the water indirectly used, via the virtual water content of other production inputs. The concept has been applied to measure the water content from surface and groundwater resources and the water content from rainfall.

To illustrate the concept, consider the example for dairy production in Australia (see box 1) — estimated to require 915 litres of virtual water per litre of milk produced (Hoekstra and Chapagain 2007). As discussed later, in practice, calculation of virtual water involves a range of measurement and methodological issues.

BOX 1: DAIRY EXAMPLE

Using milk production as a hypothetical example estimates of virtual water take into account water from all sources:

Source of 'virtual water' use	Volume of 'virtual water' used ('virtual water' litres per litre of milk)
Directly used in production	
Rainfall on to pasture	400
Irrigation of pasture	300
Stock drinking water	12
Indirectly used in production	
Rainfall and irrigation water used in production of feed grain	200
Total	915

Clearly, products that use relatively large volumes of water will have a higher virtual water content than those that do not. In the literature, most attention has been given to establishing the virtual water content of agricultural products, given that the vast majority of world water consumption is in agriculture. Estimates of the virtual water content of agricultural products reveal a wide variation between relatively low water-using products, such as wheat and rice, through to relatively higher virtual water content products, such as beef[1].

The virtual water concept is closely related to the concept of a 'water footprint'. The 'water footprint' of a country or region is defined as the volume of water needed for the production of the goods and services consumed by the inhabitants of the country or region, encompassing both the volume of water used from domestic water resources and the volume of water used in other countries to produce goods and services imported and consumed by the inhabitants of the country (water used to produce exports would appear in the 'water footprint' of the destination countries[2]).

This in turn led to the concept of 'virtual water trade' – the volumes of water embedded in the flow of exports and imports of products to and from a country or region. Indeed, as discussed below, the concept of virtual water was first used to highlight the role of trade in food products as a way of addressing water scarcity in countries with limited water resources.

2.2 APPLICATION OF VIRTUAL WATER CONCEPT IN PUBLIC POLICY DEBATE

The genesis of the virtual water concept was in the context of the economic development literature, and the observation that severely water scarce countries can reduce the pressure on their limited natural resources though trade with resource rich countries. The term was first coined in examinations of the patterns of production and trade in the Middle East (Allan 1997). Allan noticed that water scarce nations like Jordan imported water-intensive goods, and suggested that other water scarce nations could ease pressure on their meagre internal freshwater resources by importing water-intensive goods, rather than using scarce indigenous water supplies to produce goods with high embedded water content[3]. A similar argument was expressed by Fishelson et al. in the late 1980s, and the World Bank subsequently started to refer to this idea as the 'water, food, and trade nexus' in the mid-1990s.

The concept of virtual water was therefore initially used to highlight the diversity of agricultural productions systems across countries and to make the case for

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[1] See Chapagain and Hoekstra 2004

[2] See Chapagain and Hoekstra 2004

[3] The idea of developing patterns of agriculture and trade that recognise natural endowment advantages and disadvantaged has a parallel in the concept of comparative advantage, which focuses exclusively on water. In the case of severely dry nations like Jordan, the two ideas are often closely aligned, whereas in more complex production systems the determination of comparative advantage may not be so clear — this difference is explained in the following section in Section 4.2.

developing countries to import water-intensive products, rather than produce these themselves. Thus the concept of virtual water was first used as an argument against subsidisation of agriculture and self-sufficiency.

In the words of Wilchens (2007), "the virtual water metaphor was originally created to gain the attention of public officials who choose policies that influence the use of water resources in arid regions". Since the 1990s, water resource management concerns have risen up the policy agenda and have extended beyond the arid Middle Eastern and African countries. Concerns about managing water scarcity and the environmental impacts of water extraction, use and disposal are now widespread, including in Victoria and Australia.

As part of the contemporary policy focus on water resource management, the virtual water concept has been invoked in the current debate about how to best manage Australia's scarce water resources to achieve water security and efficient water use.

In particular, the virtual water concept has been adapted and subsequently applied (explicitly or implicitly) in debates seeking to influence policies and strategies on the consumption, production and trade of products that use water in their production processes, as well as on water resource and environmental management policy. Moreover, as we discuss below, the concept of virtual water has transformed from a broad focus on national resource endowments to drawing sharper comparisons between specific forms of production.

Consumption

Measures of the virtual water content of products have been used to underpin calls for encouraging or informing consumers to change their consumption patterns, away from high virtual water content products. For example, the Victorian Women's Trust (2007) recently published a document "Our Water Mark" containing data on the virtual water content of various items, including food. A major message of the report is that limiting wastage can reduce water consumption. Similarly, Rutherfurd, Tsang and Tan (2007) use the virtual water concept to present four ways that consumers can dramatically reduce their indirect water consumption:

- waste less food;
- select comparable products that use less water;
- substitute types of food that use more water for types that use less; and
- become a vegetarian.

Advocates of vegetarianism have also used virtual water in their arguments (animalsaustralia 2007), citing an estimate of the virtual water cost for each kilogram of beef of about 15,000 litres, taking into account water cattle drink, water used for pasture and hay, and service water.[4]

[4] This number for the virtual water content of beef is from a paper by Chapagain and Hoekstra (2004) and appears to be based on Northern Hemisphere beef production systems not Australian production conditions.

There have been several suggestions that consumers should be informed of the virtual water content of the products they buy. Foran (2007) suggests a water efficiency labelling scheme along the lines of energy labelling of whitegoods. "We have to get into 'water smart' shopping – whole aisles of these items, and putting labels on things." The ABS 2002 Year Book Australia features an article on 'The influence of lifestyles on environmental pressure" (Lenzen 2003).

Some commentators have even suggested that virtual water should be used as a basis for taxation (Foran 2007). "We have to start to get into instruments like an environmentally weighted GST – we can do this now at the cash register, because we know how the whole economy works in terms of every water transaction through the system".

Production

The virtual water concept has been used to call for structural shifts away from products with high virtual water content towards products with a lower virtual water content. For example, there have been calls for Australia to cease producing rice based on perceptions of high virtual water content.

The virtual water concept has also prompted researchers to suggest that overall pressure on water resources might be relieved if we locate water-intensive production processes in regions where water is abundant and where it requires less water per unit of product[5]. Some of the calls for re-locating certain agricultural industries to northern Australia have rested in part on the proposition that this would free up water in south-eastern Australia where it is seen as relatively scarce from high virtual water content products such as dairying to other activities. In considering virtual water in Victoria, Foran (2007) has canvassed whether, in order to save water, the Victorian dairy industry should be shifted to a predominantly grain diet or shifted predominantly to Tasmania or New Zealand.

Trade

In recent years considerable efforts have been made to estimate and map virtual water trade flows between countries. Rather than simply report these implied flows, however, the virtual water concept has increasingly been applied to advocate intervention in these trading patterns. For example, with 80 per cent of Australian rice, 98 per cent of cotton and 80 per cent of manufactured dairy products exported, Environment Victoria campaigner Dr Paul Sinclair says Australia is the world's fourth biggest exporter of virtual water. He says that, as the world's driest continent, Australia can ill afford to "give away" this precious commodity (The Age, 14 November 2006).

Professor Jennifer McKay has suggested that management of real and virtual water are both relevant when addressing the issue of poverty alleviation and has advocated establishing a 'virtual water trading council':

5 Hoekstra,A., 'Voices on Virtual Water', p.5

> The main aim of this council would be to ensure that the water replaced when food, electricity or industrial goods are imported is used to achieve sanitation outcomes in the importing country. The council would also ensure that the exporting country does not endanger the health of its citizens by exporting.

Water resource and environmental policy

The concept of the water footprint has also been cited as a measure of the environmental impact of water use. For example, the World Water Council (2004) suggests that:

> The virtual water content of a product tells us something about the environmental impact of consuming this product. Knowing the virtual water content of products creates awareness of the water volumes needed to produce the various goods, thus providing an idea of which goods impact most on the water system and where water savings best could be made… The water footprint can be a strong tool to show people their impact on the natural resources. Conscious people might vote for more environment friendly imports [of] goods and services.

The merits of some of these arguments are discussed further in section 4. These examples do, however, highlight the increasing use of the virtual water concept in public policy debate and the use of the concept to support some major policy changes. This highlights the need for a critical review of the concept and its ability to contribute to sound public policy formulation. To do so, there is a need to establish some key concepts of efficient resource allocation and the value of products and for greater clarity on the underling policy objectives that are being targeted, and the key prerequisites for achieving these targets.

3 Framework for analysis

The preceding quotes suggest that there is a failure to account properly for the value of water used in the production of agricultural outputs. The implication is that some water intensive forms of production, such as rice or beef, are wasteful, and furthermore that Australia is losing scarce water resources by exporting these products.

Before analysing the application of the concept of virtual water in more detail it is helpful to understand the factors that determine the price or value of a good or service. There are two key concepts that are particularly relevant to this discussion – the concept of opportunity cost, and the observation that the value of a good is determined by the demand for its properties or characteristics.

The proposition that goods are not valued for themselves, but instead are valued according to the properties or characteristics of the goods was first developed by Lancaster (1966). Characteristics of goods include the dimensions of space, form and time. For example, location is a powerful determinant of real estate values. As Lancaster points out, houses are generally more expensive the closer they are to a city's CDB. Similarly the time and form dimensions of a resource, good or service also influences its value, particularly for production processes that critically depend on these parameters. For example, a contract for the delivery of iron ore into a foundry will specify the timing of deliveries and the ore specification, both of which are critical in maintaining efficient throughput through the firm's furnaces.

The relevance of Lancaster's observation for the idea of virtual water is to highlight the importance of the characteristics of water involved in producing agricultural output. Estimates of virtual water sum all water inputs to generate a total water measure. Comparisons of relative water efficiency as evidenced by virtual water measures implicitly assume that each litre of water is equivalent and therefore direct comparisons between different outputs can be made, such as the 1,000 litres used to produce 1 kg of rice can be compared with 15,000 litres of water used to produce 1 kg of beef.

However, as we discuss later, not all water inputs are identical. Consequently, drawing conclusions based on comparisons of water totals is likely to lead to spurious results.

There are numerous sources of water involved in agricultural production systems. Some of this water may fall as rain, whereas water may be provided through irrigation or groundwater. Moreover, the time when rainfall is received within the production cycle is an important determinant of the value of the water. Rainfall that occurs when water is already plentiful, for example, follow-up rain after previous good falls is less valuable than rainfall that occurs after a prolonged dry spell. In some cases, rainfall can actually be detrimental, for example rainfall that occurs close to harvest, in which case counting this particular volume of water as equivalent to water that is available during critical times during the growing season overlooks the fact that the value of water may vary markedly through time.

The point being made here is that it is misleading to simply sum water inputs to impute the total value of water resources used to produce a product. We enlarge upon this observation in the following section.

The second and related concept that is relevant in assessing the concept of virtual water is opportunity cost. In economics, opportunity cost, or economic cost, is the cost of something in terms of an opportunity foregone (and the benefits which could be received from that opportunity). For example, the economic cost of a decision to plant a paddock to wheat would be the returns that would otherwise be available to planting the paddock to barley, or leaving the paddock in pasture, whatever is the next best alternative.

The relevance of the concept of opportunity cost for the analysis of virtual water is that the virtual water concept implicitly assumes that if the water is not used for, say rice production, that it would be available for some other activity, whether that is an input into an alternative crop or some other use. That is, the implicit assumption in the virtual water comparisons is that the water used in the production of one commodity could be used to produce something else. That is that this water has a high opportunity cost.

However, as we discuss in the following section, this may not be the case. Water is heavy and costly to transport and therefore opportunities to shift water around in response to changes in production patterns, although important in some circumstances, is not unlimited, and in some cases is completely infeasible.

Water that is available to rangeland agriculture would not generally be available to be used to support other production systems since there is no infrastructure to capture and transport this water. The implication is that this water will have little or no alternative use, or in the language of economics, this water has a low opportunity cost. As we discuss in the following section it therefore makes no sense to make a direct comparison between this water and water that has a multitude of possible uses.

Overall, it should be remembered that the underlying policy objective of water management is to the maximise value of scarce water resources — including their value to the environment — and not to minimise use of water resources per se. This has been clearly set out in Victorian policy documents with stated objectives such as to 'manage the water allocation to find the right balance between its economic, environmental and social values' (DSE 2004). Ultimately, the test of the virtual water concept is whether its application contributes to these policy objectives.

4 Assessment of the 'virtual water' concept

In assessing the merits of the application of the virtual water concept as a tool for economic and public policy analysis, two broad sets of issues can be identified:

- Issues associated with the calculation and measurement of virtual water; and
- Issues associated with its application for policy purposes.

4.1 CALCULATION AND MEASUREMENT ISSUES

There are several issues relating to the calculation of virtual water content:

- The expression of the measure;
- Assumed water intensities;
- Boundaries of production; and
- Methodological consistency.

4.1.1 The expression of the measure

As noted in section 2, the virtual water content of a product is typically expressed in terms of the volume of water of water to produce a given quantity (e.g. a kilogram) of a product (e.g. 1000 litres of water to produce a kilogram of wheat).

The 'currency' of this expression in itself imposes a number of limitations on the measure. While it is possible to compare the virtual water content measure of producing the same product (e.g. wheat or beef) in different locations, cross-commodity comparisons are difficult and potentially meaningless. For example, the observation that it takes substantially more water to produce a kilogram of beef than it does a kilogram of wheat implicitly assumes that a kilogram of beef is directly substitutable in some sense for a kilogram of wheat. Such comparisons become even more problematic when considering products other than food (e.g.

clean wool) or industrial goods or services where weight is not a relevant measure of their value in consumption.

Some attempts have been made to facilitate such comparisons by adjusting the virtual water measure to reflect the nutritional value of foods or to convert to a measure of water usage per dollar of end product value. For example, the ABS uses water use intensities (Lenzen and Foran 2001) to describe the amount of water needed throughout the whole economy in order to provide final consumers with one dollar's worth of various goods or services, or in other words, the amount of water embodied in that one dollar's worth of quantity.

4.1.2 Data issues and assumed water intensities

Exercises in attempting to measure the virtual water content of different products in different regions and aggregating these to virtual water trade flows have revealed a range of data and related issues that seriously question on the application of the concept. As noted by Yang et al (2006, p.444):

> Given the crudeness of the available data and the complexity of cropping systems in different countries, errors are inevitable in the estimation.

Moreover, as noted by Zimmer and Renault (2003):

> ..aggregating virtual water content from crop water consumption at field level up to global banquet is a path along which many assumptions must be made.

In light of these data issues, discussion of virtual water often use an assumed average technology in the calculations and this implies fixed water intensities for given products regardless of location or technology. However, different production systems and even different farms use different water volumes and sources of this water. For example, dairying in Australia is not like the Northern Hemisphere because it is grazing-based all year round and even then is based on a mixture of natural rainfall and irrigation, including irrigation water from regulated rivers and supplementary irrigation from farm dams. Grain feeding also takes place but in varying proportions, and this grain can be sourced from either dryland or irrigated cropping systems.

Using one number for the virtual water content of dairy products from all these production systems is therefore misleading. Despite this, a number of studies of virtual water appear to have done precisely this. For example, Foran (2007) discusses the Victorian dairy industry without mentioning that Victoria has a mixture of irrigated and high rainfall dairy farming.

However, reflecting actual farm-level local or even regional use of water accurately would be very costly and would lead to a plethora of virtual water measures which would be difficult to interpret and apply. This in turn raises the question whether the costs of undertaking such exercises would generate sufficient benefits to justify the effort?

4.1.3 Boundaries of production

In general, the boundary of 'water use' in the virtual water concept is limited to the farm gate. For example, in the case of dairy products, it does not include all the water required to put a litre of milk in the fridge — such as in pasteurisation, the water used to produce the steel for the dairy, or virtual water contributions from trucks and supermarkets. However, choosing the farm gate as the boundary of analysis is an arbitrary decision, and excludes some significant elements of water used in overall production and consumption.

4.1.4 Methodological consistency

There is no uniform methodology for calculating virtual water estimates. In the various studies available, little convergence exists with respect to the general approach taken. Differences occur in the treatment of several issues including (Hoekstra 2003):

- virtual water content of a product at the production site;
- the hypothetical virtual water content if the product would have been produced at the place where the product is actually consumed;
- measurement at field level, rather than the point of water withdrawal;
- inclusion of the losses between water withdrawal and application; and
- different methods of attributing water inputs into intermediate products to the virtual water content of the final product.

Recognition of the wide range of different methodological approaches and assumptions that have been adopted in the virtual water literature to date has led to calls for these to be standardised and further refined in some areas. Some commentators (World Water Council 2004, p.21) have even suggested that:

> Governments and international organisations should include 'virtual water' accounts as an instrument in any national or regional water and agriculture policy analysis. Common procedures and standards should be developed and determined. To enable introduction of virtual water as an instrument, virtual water accounts should be developed to support any national or regional water and agricultural policy analysis….
>
> There is a very real need for more research on the prescriptive potential of the virtual water theory and on the potential of virtual water trade to relieve pressure on the globe's water resources and to achieve food security in the world's water-scarce regions. To make the concept of virtual water helpful in policy making, the concept itself needs to be further clarified and the difference with common food trade must be made more explicit.

Before proceeding down this path, however, the fundamental question to be asked is whether, even if the various data and methodological issues could be addressed and agreed, whether the effort and resources required to do so would be justified. This turns on the issue of the underlying value of the concept as a tool to improve economic and public policy on water resource management.

4.2 LIMITATIONS ON ITS APPLICATION FOR POLICY PURPOSES

The fundamental limitation of the virtual water concept in guiding production and consumption decisions is that it does not provide any context or differentiation between the various volumes of water that are aggregated, and the alternative uses for which these could have been used. This is true for volumes that are added up across a production process, as well as for volumes compared between different production processes.

This 'water is water' approach ignores the opportunity cost of the volumes of water used — the best environmental, social or economic use it could have been put towards if it were not used in the given production process.

Water can be used in many different ways and the opportunities for its use vary according to where and when the water occurs. For example, rain falling on the plains in a rural landscape will be:

- Used for evapotranspiration by a suitable crop that has been planted on that land, or
- Evaporated or evapotranspirated on vacant land or grassland.

This is starkly different to water held in storage in dams, from where the water may be applied to a number of different irrigated crops, used to supply rural towns with urban water, or held back to secure water for future use. This is again different to tap water in an urban setting that is already treated and made suitable for drinking as well as a range of industrial processes.

The key difference is the range in values of the opportunities presented by these alternative uses. In some cases, the value of the alternative use is near zero (where it would have evaporated), or it can be high — in 2007-08 the price of temporary irrigation water in the southern MDB exceeded $1200/ML — or it could be extremely high for water used to secure reserves for basic human needs.

This variation in the opportunity cost of different volumes of water is sometimes acknowledged in some of the virtual water literature. Hoekstra and Chapagain (2007, pp. 46–47), for example, note tellingly:

> Also one has to realise that some parts of the total water footprint concern use of water for which no alternative use is possible, while other parts relate to water that could have been used for other purposes with higher added value. There is a difference for instance between beef produced in extensively grazed grasslands of Botswana (use of [rainfall] water without alternative use) and beef produced in an industrial livestock farm in the Netherlands (partially fed with imported irrigated feed crops).

However, these important caveats are seldom brought to the fore in the presentation and analysis of virtual water estimates – or when drawing policy conclusion from such analysis.

A number of issues may impact on the opportunity cost of water. These include:

- Differences in water resource types;
- Differences in water resource locations;

- Differing roles of water in production; and
- Differences in water scarcity and resource stress.

Differences in water resource types.

There are significant differences in the various sources of water, each with consequences for when and where water can be used. These affect opportunity costs — and the ability to alter the locational and timing characteristics mean that more alternative uses for the water may be available (which can potentially increase the opportunity cost of this water).

- Rainfall — may be used where it falls and some may runoff into surface water systems or recharge groundwater systems.
- Surface extractions — may be unregulated systems that allowing extraction at only one time for a given location, or may be a regulated system that permits water to be 'delivered' (released from the dam) at a desired time.
- Groundwater extraction — there may be aquifers that underlie large areas, and may or may not be closely connected to surface water systems in the region.

Location of water use

Water is a very bulky resource and hence is costly to transport, so that use in one location is often not readily substitutable with another location. Consequently, the alternative uses for water are often bound tightly within the geographic region of the water resource, and the opportunity cost of water between regions can vary due to different sets of alternative uses.

When it is possible, the usual mechanism to shift water between areas is gravity — either in rivers or irrigation channels. The connected system in the southern Murray–Darling Basin is an example where water is reallocated between a range of possible uses. Moving water between locations can have significant environmental effects. Water trading rules demonstrate how this reallocation can occur — including significant environmental and hydrological constraints.

In some circumstance water can also be pumped between locations, however this is costly in terms of the infrastructure and energy required.

Differing roles of water in production

Water is one of many inputs in the production of goods and services. For example, the estimated share of irrigation costs as a percentage of total costs is highest in rice (16 per cent) and dairy (14 per cent), and lowest in grapes (3 per cent), vegetables (2 per cent) and fruit (1 per cent) (CSIRO 2002). Agricultural production also requires land, labour and machinery as well as other inputs like fertilisers and fuel.

There may be interactions between these inputs. Complementary relationships between inputs are common in agriculture — applications of one input (such as fertiliser) are best matched with increased applications of other inputs (such as water). Substitution possibilities may exist between water and other inputs — the use of water-saving irrigation schedules requires more labour, or capital expenditure is required to reduce delivery losses in an irrigation system. In fact, on-farm water savings alone are unlikely to justify investment in water saving technology — labour savings and yield or quality increases are valuable complementary benefits of the technological change (Appels, Douglas and Dwyer 2004).

Other studies have noted the significant deficiencies of measures that ignore the role of inputs other than water in production. For example, Douglas, Dwyer and Peterson (2004) on the limitations of activity gross margins such as those expressed as gross margin per ML, and Productivity Commission (2006) on the significant difference between measures of technical and economic efficiency in rural water use.

The concept of virtual water does not account for other inputs used in production nor acknowledge that trade-offs exist between these inputs. Indeed it effectively assumes that water is the only scarce factor of production and tends to promote policy prescriptions that focus exclusively on considerations of how water should be allocated between activities and locations, regardless of the impact on (and cost of) other inputs. Efficient production requires that resource use decisions be maximised across all inputs, whereas the concept of virtual water implies that water use savings should be pursued regardless of cost.

Rather than rely on flawed and partial measures such as 'virtual water', Edwards (1976, pp. 189–90) concludes:

> The use of market prices for inputs of natural resources, labour, capital and energy seems to be the only satisfactory way of deciding which products to produce and what combinations of inputs to use in producing them…Where product or input prices do not reflect social value or costs accurately it may be desirable to introduce policies which change prices to consumers and/or producers. This is far removed from abandoning market determined prices and substituting an alternative criterion of benefit and cost.

Setting research priorities in terms of the virtual water content of commodities is another potential policy error that could result[6].

Water resource stress and environmental condition

Virtual water does not recognise whether water use is within sustainable limits of extraction, or otherwise. It does not inform users of the concept if the alternative use of the water would be for a very valuable environmental use — such as in a system that is severely stressed by over-extraction and facing degradation to an unacceptable level. A simple example can illustrate this (see box 2).

[6] Virtual water shares such criticisms with the concept of energy budgeting. Edwards (1976) found that the "consideration of energy/food price relationships in a price responsive, trading world indicated a need for great care in assessing the effects of higher energy prices and in drawing policy implications, for example for future production patterns or for research priorities, from energy ratios. They indicate, for example, that … suggest[ions] that special emphasis should be given to research aimed at maximising energy ratios in crop and animal production is naïve" (p. 189).

BOX 2: WATER USE IN DIFFERENT REGIONS

Suppose that we are comparing perennial pasture produced in two regions, A and B.

In region A, water resources are under pressure and are currently being used at levels beyond those which are ecologically sustainable. Given this pressure, however, producers have adopted production techniques that seek to minimise water use, and can produce a kilogram of pasture using 80 litres of water.

In region B, there are abundant water resources and their use is managed to ensure no adverse impact on the environment. In this region, a more water-intensive technology is adopted, resulting in a virtual water measure of 110 litres of water per kilogram of pasture produced.

Analysis based on virtual water would suggest that the environmental impact of water use in region B was much higher in region B than region A, when in fact the reverse is true.

A real-world example is provided by Facon, quoted in World Water Council (2004, p.11):

> In Thailand, a number of experts are concerned that Thailand through its rice exports, is exporting a lot of virtual water, they had rather this water be put to more productive uses, such as industrial production. Now, in practice, for Thailand as well as other humid monsoon countries, most rice is produced in the rainy season where one has rather too much water than not enough. Reducing rice areas would lead to more flood damages, reduced groundwater recharge, etc. There is more tension on water resources in the dry season, but allocation rules ensure that agriculture is the last served, after other sectors. So, even if a large proportion of water resources is virtually exported, should we think that something should be done about it? Just looking at the virtual water trade figures, which aggregate quantities of very different types of virtual water, may be quite misleading.

Returning to Hoekstra and Chapagain's (2007) calculation of the water footprint of various nations, the total virtual water consumed by Australians (the water footprint) was 1.4 ML per capita per year compared to 0.7 ML per capita per year for China. The concept of virtual water or the water footprint sheds no light on environmental conditions in either country. Despite its low apparent 'water footprint', serious water and land degradation is observed in China.

It follows that the concept of virtual water does not provide any useful information about the appropriate times for government to be involved in environmental management (such as when too much water is extracted from rivers and groundwater, occasioning environmental damage to river health, or when irrigation has adverse downstream effects). Virtual water tells us nothing about who should pay for environmental remediation. Virtual water does not provide any useful information when it comes to measuring, monitoring or repairing environmental damage.

In the Australian context, the opportunity cost of water is likely to vary significantly. Contrary to popular belief, Australia is well endowed with water in terms of its population even if the water is often in the wrong place at the wrong time. Important features of Australian water resources are elaborated in textbooks by Pigram (2006) and Smith (1999) (see box).

BOX 3: AUSTRALIA'S WATER RESOURCES

The following extracts from these two standard works demonstrate why average measures of virtual water that do not account for variability of water supplies in space and time are fraught.

> The general aridity of the Australian continent is confirmed by the low average annual run-off of 420 millimetres, compared with a world land-surface average of 660 millimetres (Pigram p.19).
>
> Fortunately for Australia, this poor natural endowment is matched by an exceptionally low population, and…the amount of water, per person, ranks among the most favourable on Earth. In this regard, water, like Australia's mineral resource potential, seems to confirm our status as the 'lucky country' (Smith p.16).
>
> The seasonal distribution of rainfall varies greatly over the continent with the most obvious features being a clearly defined summer maximum in the monsoon region of northern Australia and a marked winter maximum in the south-west and south-east (Pigram p. 20).
>
> Apart from the large areas of Australia that experience relatively low rainfall, a further distinguishing feature of the precipitation pattern is its unpredictability and unreliability (Pigram p.20).
>
> …the hydrological extremes in Australia put the wisdom and validity of hydrological assessment methods derived from temperate, mid-latitude, northern-hemisphere sources in doubt (Smith p.16).
>
> It is clear that, in terms of population, Australia is well-endowed with water. For many of the major drainage divisions, less than 5 per cent of divertible flows have been developed for use. It is equally clear that most of these untapped water resources are in the wrong place; they are well away from both centres of population and from the more productive agricultural land. However, there should be no fear that, on any feasible time scale, water will be a factor limiting population growth. Our untapped resources are the envy of most of our Asian neighbours, of heavily populated regions in North America, and of virtually the whole of Europe (Smith p.341).
>
> Australians must accept the fact that their continent can be both a very wet and a very dry land. Droughts and floods are naturally recurring phenomena and must be taken into account in the planning and management of land and water resources (Pigram p.39).
>
> It has always seemed strange to me that accounts of future domestic water supply in Australia are so full of doom and gloom (Smith p.342).

Virtual water and comparative advantage

Comparative advantage is a concept related to opportunity cost that shows how trade is beneficial between countries that have different opportunity costs of production. Comparative advantage is a fundamental component of international trade theory. In essence, nations (or regions) can gain from trade if they concentrate or specialize in the production of goods and services for which they have a comparative advantage while importing goods and services for which they have a comparative disadvantage. However, it is important to note that comparative advantage is not only based on the resource endowments of a country — water, land, etc — but also the production methods that can be used to convert these resources into goods and services.

It may be the case that extremely dry countries such as Jordan can benefit from importing agricultural products because they may have a comparative disadvantage at producing water intensive crops.

However, because virtual water measures only the water resources used, and not the other resources or production technology used, it cannot be used as a proxy for comparative advantage. In fact, it may give exactly the wrong answer to the detriment of the home country and its trading partner (see box).

For example, despite dairy production having a high virtual water content, DPI considers Victoria's dairy industry to be "internationally competitive because of its low cost pasture-based systems and clean green (environmental) image". This is because "Victoria's temperate climate and natural resources enable year round grazing of quality pastures grown using relatively low cost irrigation water or with rainfall alone" (DPI 2007). Also, the use of new or improved technologies have enabled milk production to increase by 5% per year.

These views on dairying in Victoria based on consideration of all the resources available for agricultural production and market opportunities contrast markedly with the views expressed by Foran (2007) based on the concept of virtual water. Foran suggests that in the dry conditions of the mid-2000s the question arises whether to change the Victorian dairy industry to a predominantly grain diet and so put pressure on grain areas but save water, or whether to shift it predominantly to Tasmania and New Zealand. Such an analysis ignores many important factors, because water is not the only scarce resource.

Further, comparative advantage is related to comparative endowments of various resources (and the way in which these resources can be used). For example, Hoekstra and Chapagain (2007) found that the total virtual water consumed by Australians (the water footprint) was 1.4 ML per capita per year compared to 0.7 ML per capita per year for China. However, the same data source shows that the total water use *available* to Australians is 5.2 ML per capita per year compared to 0.8 ML per capita per year for China. In a per capita sense, Australia is well endowed with water.

BOX 4: VIRTUAL WATER AND COMPARATIVE ADVANTAGE

Wichelns (2007) presents a simplified example that demonstrates that optimal strategies are not always consistent with expectations based only on the concept of virtual water. This example shows that a water-short country might gain by exporting water-intensive crops and importing crops that require less water per unit of production.

Consider two countries with different endowments of water and different conditions for agriculture, and with linear production functions. Country A has 5GL of water resources, that is sufficient to irrigate 500 ha of cotton (yielding 600t of lint) or 750 ha of wheat (yielding 2400t of grain) — this means that the opportunity cost of using the water to irrigate cotton to produce 1 tonne of lint, is the foregone production of 4 tonnes of wheat. Country B has poorer soils and climate for agriculture with 10GL of water resources, that is sufficient to irrigate 1000 ha of cotton (yielding 800t of lint) or 1500 ha of wheat (yielding 4000t of grain) — this means that the opportunity cost of using the water to irrigate cotton to produce 1 tonne of lint, is the foregone production of 5 tonnes of wheat. This means that Country A has a comparative advantage in the production of cotton, and Country B has a comparative advantage in the production of wheat.

If the two countries specialise in the products they have a comparative advantage in, a total of 600t of cotton lint and 4000t of grain can be produced, whereas without specialisation the total water resources of the two countries cannot be used as productively (see table).

	Specialisation			*Producing 600t cotton*			*Producing 4000t wheat*		
	A	B	**Total**	A	B	**Total**	A	B	**Total**
Cotton (t)	600	0	**600**	300	300	**600**	100	400	**500**
Wheat (t)	0	4000	**4000**	1200	2500	**3700**	2000	2000	**4000**

The result is based on the fact that a country can benefit from specialising in those goods it has a comparative advantage in, and engaging in international trade. A country will not necessarily have an comparative advantage or disadvantage in producing water intensive goods based purely on water availability, because availability of the other resources and production relationships can differ.

Virtual water is constructed essentially on notions of resource endowments. In contrast, as demonstrated in this example, this is not the same as the pure principle of comparative advantage.

5 Conclusions

Policymakers are legitimately interested in ensuring that as a society we make the best use of the available water resources. An equally valid concern of policymakers is that production systems are sustainable and that environmental impacts are properly managed and accounted for within agriculture.

Virtual water is a measure of the total water used in production of a good or service. In some quarters the development of virtual water estimates has been promoted to guide policy makers' decisions on these matters. However, as this paper demonstrates, the virtual water concept offers no effective guidance to policy makers regarding either water use efficiency or the sustainability of water use. While the concept is simple, and hence superficially appealing, its simplicity also lies at the heart of its deficiency as a tool for economic and public policy analysis.

The key deficiency of the virtual water concept is that it does not take into account the opportunity cost of using water — the value of alternative uses for which water could have been used — nor other inputs used in production. The opportunity cost of water varies significantly due to locational and timing differences of different water sources, and water's relationship to the other inputs in production.

- This means that virtual water cannot shed any light on strategies to use water resources in a way that maximises the benefits of this water use.
- This means that virtual water cannot inform environmental considerations because it cannot by itself shed any light on whether water resources are being used within sustainable extraction limits, or otherwise.
- In general, any reliance on the virtual water concept would promote arbitrary, and inefficient policies, and lead to undesirable decisions by government.

Devoting attention to further refining and applying the virtual water concept is also likely to divert attention and resources from addressing the real policy issues. There has, however, been substantial progress in the development of policy instruments that promote efficient water use. Ensuring water prices reflect the true cost of the resource and policies that allow water to be reallocated to higher value uses have been key initiatives. It is possible that there are further opportunities available to improve the flexibility of water utilisation. A focus on understanding and/or removing these impediments to water reallocation is likely to be a better investment than attempts to refine virtual water estimates.

Similarly, further investment in virtual water estimates will not improve our understanding of environmental consequences of agricultural systems. To effectively address environmental and sustainability issues, policymakers require information which directly links farming activities with environmental harm. This is not provided by virtual water estimates, and as we show in section 4.2, reliance on virtual water measures could lead to conclusions that produce unfavourable environmental outcomes.

There is no reason to depart from the general principle that the economic (cost-benefit) basis on which policy decisions should be based are the actual prices observed in the market. If there are good reasons for altering those observed prices, adjustments can be made with the reasons for the changes made transparent. Relying on problematic calculations of the virtual water content of commodities will not improve on this general approach.

In summary, virtual water has little to say about policy issues surrounding the allocation of scarce water resources.

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