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A Method for Estimating the Potential Trading of Worked Water among Multiple Mines

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Abstract In many parts of the world, mine production and expansion are increasingly limited by access to water. One solution is to consider a water market that would allow trading of mine site water (worked water) from wetter mines to drier mines. However, there is currently no policy support for such a market and it is likely that without government support via incentives, mines will continue to favour freshwater use because it is relatively inexpensive. Furthermore, mines have a high capacity to pay for the water they use, and freshwater creates few risks for production. The opportunity provided by water savings within a trading scheme could be viewed as a source of money to provide incentives for the transfer of worked water between mines. In this paper, we present a new method to trade water among mines based on a site water balance assessment utilising historical climate data, and apply this method to a demonstration region containing multiple coal mines. On average, 340 ML could be transferred per year to drier mines but there remains 11,440 ML per year of water demand unable to be met by trading. The direct monetary value of the worked water that could be transferred, derived from additional coal mining, would be significant. Irrigation may be an attractive option if available infrastructure can be used to trade the saved fresh water in existing markets, thereby providing indirect monetary value (i.e. external to coal production). Alternative uses of water savings may have considerable additional non-monetary value that directly affects the mining industry's social license-to-operate and its security of long term water supply.

Keywords Mining · Sustainable development · Water resources · Water trading

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Introduction

Over the last three decades, global environmental change has rapidly intensified. This includes all the major human induced impacts on natural ecosystems, such as extensive vegetation clearing and deforestation, changes in atmospheric composition and climate, altered surface hydrology, river flow and ground water availability, soil organic matter loss, and siltation of rivers and receiving waters (Bonan 2008). In response to this decreasing availability and increasing competition for water resources in regions, many governments world-wide have put in place mechanisms for the allocation of water to different uses. On the one hand, governments can legislate the allocation of water on the basis of societal need. Alternatively, water markets allow potential users to determine allocation of water based on willingness and capacity to pay. However, water markets do not take into account the 'true' value of water, which is a function of both the private and public goods and services it provides (Barrett 2009; Evans et al. 2006; Moran 2006; Moran et al. 2008, 2009). As a consequence, various charging and cost recovery policies and mechanisms are also implemented by governments to recover external costs.

A number of methods have been proposed to estimate the monetary value of water. The simplest approach is the ratio of gross margin to volume of water used, generally expressed in terms of $ per unit volume (the 'productivity ratio'). Other metrics of water value incorporate the flux of all water that passes through a production process. For example, a piece of woollen clothing is represented by the total water flux including feeding sheep, generating power for all aspects of sheep husbandry, transport of all intermediate products, that is, all such embodiments on all the components of a jacket, for example. When summed over all water fluxes, this metric is called 'embodied water' and it represents the value added at each stage of the production process to provide an overall valuation of the water used in production based on the total flux of water used to produce the commodity. However, this method of valuation can be potentially misleading because it doesn't separate water consumed in the production process (thereby becoming unrecoverable) from water that is recovered and used for other value creating purposes (e.g. Younger 2006). In other cases, it is used as a way to indicate that water has value beyond the unit market price, e.g. in understanding implications of international trade in virtual or embodied water (Yang et al. 2006). Another approach is to estimate the optimal value of the joint production of environmental goods and services using shadow price methods (Diaz-Balteiro and Romero 2008). This approach has the advantage of being able to determine an efficient allocation of resources to production and to express the production of goods and services in the same units as the water market. An alternative approach is to express the value of water in terms of the risks that a business might face when choosing one water supply or security option over another (Moran et al. 2008) or to comprehend how water relates to the goals of sustainability (Moran 2006). These different approaches are important when considering the efficiency of water allocation in the wider context of environmentally sustainable development. Maintaining water security in the long term requires developing a 'strategic view' of water management that also considers the non-monetary value of water. A strategic view takes account of community concerns over water supply and quality, company social responsibility relative to water use, and requires an understanding of the relationship between water allocation, the need for water, and the capacity to pay for water by different sectors of society (Barrett 2009). Insufficient awareness of these non-monetary values of water represents risks to production in both the short and long term. These risks are manifest through security of water supply, changes in water entitlements, increasing legislative requirements, and higher costs of compliance, supply, and discharge. Poor strategic management of water will ultimately lead to marginalisation of the industry from public policy development and community debate, thereby threatening long term access to water with subsequent impacts on mine expansion and establishment.

All water allocation policies focus on fresh water, either under regulated or 'natural' flow conditions. Therefore, regardless of the valuation driver or mechanism of estimation, water value is only considered in terms of fresh water. Consideration only of freshwater ignores potential efficiencies across any hydrological domains associated with reallocation or sharing of non-fresh water (herein termed 'worked water'). We are unaware of any government policy that is aimed at encouraging the exchange of worked water. As a result, worked water is not valued monetarily because it is excluded from the water market and therefore it is not an attractive commodity for trade. Without incentive to trade, it is often cheaper to evaporate worked water and to import fresh water than to attempt to exchange worked water among potential users. However, incentives could be developed by considering the minimum value of worked water to be equal to the value from the equivalent volume of fresh water it replaces that can be put to an alternative use (less costs associated with transport and treatment of water). The benefit is even greater if this fresh water can now be redirected to a higher value use. This would increase regional 'total water productivity' because every unit of worked water that is reused generates income in addition to the income generated in its first use. In regions where multiple mines are operating in close proximity, the differences in relative 'wetness' and 'dryness' of mines compared to their operational needs could be exploited as an opportunity to exchange worked water. However, with no incentives available, if fresh water remains less expensive, the opportunity to increase total system water productivity is lost.

In this paper, we present a new method for assessing the potential of worked water sharing across a group of mines operating within a single geographical domain. The potential for worked water sharing is computed based on defining an acceptable level of risk to each operation of being not 'too wet' or 'too dry' in a statistical sense. This permits estimation of the potential for value creation from the fresh water that could be used for other purposes. The final result is a calculation of the difference in total water productivity with and without worked water exchanges and an estimate of the size of subsidy that would be needed to make this viable. We finish with a discussion of the 'true' value of worked water traded among mine sites.

Methods

Sixteen coal mines were selected within a demonstration region for this analysis. To maintain confidentiality of individual site-level data, the location of the region is not disclosed and actual costs have been altered. This does not affect the illustration of the concept. A water balance was developed for each mine that describes the fluxes between various mining and commodity-concentrating tasks, the size of site water stores and the site inputs (e.g. pipeline, rainfall interception, and run-off) and site outputs (e.g. discharge). The system model employed for this, *Water-Miner*, has been previously described (Cote et al. 2006). The historical precipitation and evaporation data for the region was used as model input to drive a simulation of the water balance over a period of years (generally, 50 years of historical data were used). This produced a time series of volumes of worked water held on site. A worked water storage exceedence function was then derived from the time series of volumes of worked water in stores (Cote et al. 2006). This exceedence function describes the proportion of time that the worked water store exceeds a given proportion of storage capacity. Figure 1 illustrates exceedence curves for various mines in the demonstration region. A site that is most often too dry has as high risk of losing production due to insufficient water. Conversely, a site that is most often too wet risks penalties associated with discharge. Another pathological case is a site where the storage capacity is not matched to the local climate variability (e.g. too little storage capacity) and rapidly switches from too dry to too wet (or vice versa) as climate varies. A desirable system is one that is infrequently too wet (i.e. >90% full infrequently) and also not too dry (i.e. not <25% full too frequently).

Two indices were derived for each site from the exceedence curves. These are:

1. A 'wetness' index (W_i), defined as the percentage of time for site i that worked water storage exceeds 90% full; and,

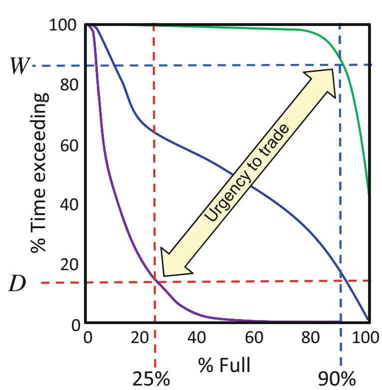

Fig. 1 An example of worked water 'exceedence curves' for 3 mines in the demonstration region. The concave curve (*purple*; LHS) is from a site that is too dry, too often. The convex curve (*green*; RHS) is from a site that is too wet, too often. The curve running from *top left* to *bottom right* (*blue*) is from a site that has its water supply and water demand requirements in balance. The 'urgency to trade' water between mines is depicted as the distance on the exceedence graph between the wetness, *W*, and dryness, *D*, indices for any pair of sites

2. A 'dryness' index (D_i), defined as the percentage of time that worked water storage is at least 25% full.

From these indices, it is apparent that an incentive exists to trade water between mines in situations where W_i is high and D_i is low. This is termed the 'urgency to trade' between sites i and j and is expressed as:

$$U_{i,j} = \left| W_i - D_j \right|.$$

For any site, the 'need to sell' water to any other site is defined as:

$$S_{i,j} = W_i \, U_{i,j},$$

and, similarly, the 'need to buy' water from any other site is:

$$B_{i,j} = D_i U_{i,j}.$$

With these definitions, the $S_{i,j}$ and $B_{i,j}$ represent an individual mine's water status with respect to every other mine within a region and provides a basis for establishing the priority or order in which water trades can occur among sites providing that enough water is available to trade. However, mines are less likely to trade the further they are apart. So, we calculate the 'propensity to trade' index among mines, $P_{i,j}$, which takes into account the need to sell and buy water as well as the Euclidean distance, d, between mines;

$$P_{i,j} = \frac{S_{i,j} \, B_{i,j}}{\left\| d_{i,j} \right\|}.$$

In the present case, we normalised d to the maximum distance among mines within a region. While this takes into account increased costs associated with transporting water across distances, it does not take into account infrastructure, pumping, treatment, monitoring, and management costs associated with water transport. The 'propensity to trade' function can be adjusted in the future to incorporate these costs.

Finally, an operating target value for the mine worked water storage must be set. This can be determined individually for each mine depending on local requirements and management approaches. Here for simplicity, we assumed that a reasonable target for wet sites was to sell water that represents the difference between median volume (i.e. the volume of worked water that a site would be expected to have 50% of the time) and the volume at 90% full. Similarly, it was assumed that the target for dry sites was to purchase water that represents the difference between median volume and the volume at 90% full. The 90% target represents a water storage that ensures all water requirements of production are met while also avoiding discharge due to a chance high rainfall event. An example of the sale and purchase of water for two mines is shown in

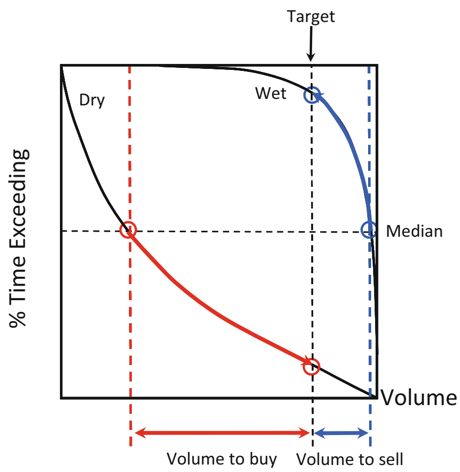

Fig. 2 A schematic of the sale and purchase of water between two mines. For simplicity, both mines have the same volume storage capacity. *Solid black lines* show water exceedence curves for a 'dry' and 'wet' mine. The median storage is defined as the volume of the worked water store 50% of the time (*horizontal dashed black line*). 'Wet' mines sell water (*blue arrow*) until the volume drops to the target storage value (*vertical dashed black line*). 'Dry' mines purchase water (*red arrow*) until the volume reaches the target value. In this case, volume to buy > volume to sell and additional trades are needed to fully satisfy the demand for water by the 'dry' mine

Fig. 2. The algorithm for conducting trades consists of ranking the $P_{i,j}$ and proceeding to trade volumes of water from site $i \rightarrow j$ until there is no more water available to trade. The total volume is calculated as the sum of all trades and unmet demand or untraded surplus is recorded.

Results and Discussion

A matrix of propensity to trade values for the 16 demonstration mines is shown in Table 1. From the table it can be seen that many mines have little propensity to buy or sell. Figure 3 shows the spatial distribution of these mines within the demonstration region, the $P_{i,j}$ values for particular sites and the amounts of water traded for this particular case study. For this demonstration region, a total of six water trades were undertaken from 'selling' mines (7, 10, 13, 14, 15, and 17), which were purchased by two mines (9 and 16). Following completion of the trades and taking into account water volumes available/needed, a total of ≈340 ML were sold with 11,440 ML of unmet need. On average, this region does not have sufficient excess water to meet the water supply needs across all mines. Given this situation, there would appear to be some rationale for sites to increase water storage capacity to hold more water when it is available from infrequent but significant rainfall events. This would allow exchange of water among sites allowing all sites to maintain sufficient capacity for production. In addition, the cost of infrastructure (e.g. pipelines and pumps) may be cheaper for small sites than the costs of dam construction. However, where this infrastructure already exists, these costs are avoided, increasing the value of the water traded. In this case study, even the modest exchange of 340 ML provided an opportunity for considerable monetary value to be generated within the coal industry in this region.

Table 1 The 'propensity to trade' matrix for the demonstration region of 16 mines; the 'sell' cells are shown in italics; the mine numbers identify mines in the water accounting database

	SELL																
	Mines	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
BUY	2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.1	0.0	0.1	4.1	0.0	5.2	0.0	0.0	3.4	0.0	0.0	0.2	1.9	1.9	0.0	2.0
	4	0.0	0.0	0.0	0.1	0.0	0.4	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.2	0.0	0.2
	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.0	0.0	0.1	0.9	0.0	2.9	0.0	0.0	2.0	0.0	0.0	0.2	1.5	1.5	0.0	1.6
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.0	0.0	0.0	0.2	0.0	1.3	0.0	0.0	1.0	0.0	0.0	0.2	2.2	2.4	0.0	2.0
	9	0.0	0.0	0.1	1.0	0.0	13.3	0.0	0.0	13.2	0.0	0.0	0.6	4.8	4.4	0.0	5.2
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	0.0	0.0	0.0	0.4	0.0	2.4	0.0	0.0	1.4	0.0	0.0	0.5	5.6	6.2	0.0	5.2
	12	0.0	0.0	0.0	0.2	0.0	1.3	0.0	0.0	0.9	0.0	0.0	0.2	1.9	1.9	0.0	1.8
	13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	16	0.0	0.0	0.1	0.6	0.0	5.5	0.0	0.0	2.5	0.0	0.0	1.4	8.9	7.3	0.0	11.7
	17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

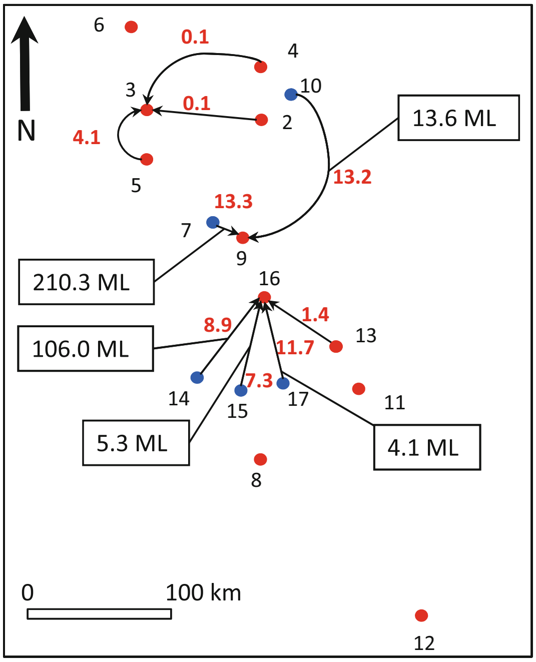

Fig. 3 The spatial distribution of mines within the demonstration region (*symbols*) and direction of potential water trades among mines (*arrows*). *Red symbols* represent mines that need to buy water to meet a target of 90% worked water storage capacity. *Blue symbols* represent mines having worked water storage in excess of 90% capacity. *Black numbers* correspond to mine identification and *red numbers* refer to $P_{i,j}$ values from Table 1. Numbers within boxes refer to actual volumes of water traded among mines totalling 340 ML

An estimated coal gross margin of AUS$18.6 k per ML (ACIL Tasman 2007) indicates that a potential gross margin of $6 m p.a. is possible from these water trades. However, the ACIL Tasman (2007) report was not based on water use figures for this region and may include water reuse in the calculation of gross margin thereby inflating the average water productivity ratio. To provide another assessment of the monetary value of this saved water we used figures for the imported fresh water component of use for mines in this region (Moran et al. 2006). In terms of revenue for coking coal (rather than gross margin), with an average fresh water requirement of 210 ML/Mt (Moran et al. 2006), the 340 ML transferred could be used to mine an additional 1.5 Mt coal. At a selling price of $120 per tonne, the water "traded" could be used to generate ≈$AUS180 m of revenue per annum. On the other hand, competitive disincentives to trade water might occur in situations where the market is distorted or where a monopoly occurs. For example, in a situation where water deficits restrict regional production in 'dry' mines, it may be advantageous to a 'wet' mine not to trade, thereby benefiting from any higher prices generated by reduced supply.

In terms of the monetary value of water savings, the next most profitable industry to coal mining is irrigated agriculture. It is important to recognise that the fresh water

Table 2 Gross margins from a range of irrigation products in Australia (adapted from Moran et al. 2008)

Commodity	Mean gross margin ($AUS'000/per ML)	Margin ($AUS '000) from 340 ML
Pasture (livestock)	0.075	24.3
Rice	0.125	40.5
Dairy	0.32	103.68
Cereal	0.135	43.74
Annual row crops	0.225	72.9
Vegetables	1.100	374
Vine & tree fruit	0.450	153
Viticulture	1.300	442

saved from mine water trading is extracted directly from a regulated water resources management system where off-takes could relatively easily be switched to service irrigation requirements with little or no marginal cost to irrigators. This switch can occur both upstream and downstream of mine off-takes. Gross margins for a range of irrigation products are shown in Table 2 along with the gross margin from an additional 340 ML of fresh water that could be made available to irrigated agriculture. The most profitable water use (viticulture) would return a gross margin of 7% of coal production. In this region, temporary water trades can range from $AUS30-300 per ML, with more trades at the lower end. Based on this, it is unlikely that potential revenue from trading water from coal mine allocation to irrigation would, on its own, make the transfer of worked water between mines attractive. However, it is possible to consider a government intervention that would make these transfers sufficiently attractive for mining companies to consider worked water rather than fresh water use. For example, a one-off government infrastructure grant could be used to link those mines having the greatest potential for worked water exchange. Whilst not as profitable as coal production, there is still considerable scope for additional value to be generated by exchanging worked water between mines to achieve fresh water savings. Precedents for such infrastructure grants to save fresh water in other contexts already exist in the irrigation and urban sectors in Australia. In some cases, the presence of existing pipeline infrastructure such as in the Hunter Valley, New South Wales, and the Bowen Basin, Queensland, has already facilitated water trades between mines during periods of severe drought. Furthermore, in the Republic of South Africa, mining companies have entered the water market through private–public investments in water treatment thereby contributing to the supply of potable water to a local municipality and benefiting from the value of reduced regional water competition (Gunther et al. 2006).

Given that coal generates the greatest return per unit of water, it may appear that little imperative exists to trade water outside the mining sector. However, the availability of existing infrastructure to transfer water to irrigation sites may make the lower return to irrigation a viable option, particularly when non-market value of water is taken into account. For example, the community engagement associated with returning fresh water allocations to irrigation, other production sectors, environmental flows, or gifted to parks, sportsgrounds and gardens may have value to the mining industry in terms of the social license-to-operate in excess of its direct monetary value from coal production (Barrett 2009). Increasingly, an adaptive management approach is required by mining companies to deal with water issues, particularly in the face of supply variability. This adaptive approach needs to be capable of diagnosing problems, incorporating learned behaviour, and accommodating changes in the external physical, social, regulatory, and economic environment into the decision making process. It needs to balance short term needs of water for production with long term access to water for mine expansion. It also needs to take into account the complex interactions associated with water use across multiple sectors of society (Barrett 2009). An important component of adaptive management is assessing the true value of water to mining, which requires:

1. Calculating hidden and indirect costs of water, and incorporating these into the business case for water management decisions;
2. Assessment of the risks and uncertainties associated with water management decisions; and,
3. Understanding the differing needs for water among sectors of society relative to the disproportionate income of these groups that may act as barriers of entry into a water trading market.

The savings in fresh water achieved through trading worked water among mines in this region represents a potential reduction in hidden costs, reduced uncertainty, and risk of water supply, thereby contributing to reducing community concerns about water resources issues. The value associated with these benefits are not related to the direct monetary value derived from immediate coal production but they do have long term monetary benefits in supporting ongoing production, mine expansion, and access to new development sites, and are also nonetheless important to achieving sustainable development goals.

In any region where a water trading system among multiple coal mines is potentially feasible, the particular circumstances that would generate a successful scheme will be contingent on a multitude of local conditions. In this analysis, we have not considered many factors that would be required to create an active and viable worked water trading regime. In some cases, water transfer infrastructure may already exist close to mines that may wish to trade. If there are regulatory or other constraints, such as access to land or supply of energy for pumping, these may favour water trading within or between a subset of sectors in society. In the method developed here, such additional factors could be added to the propensity to trade matrix without much difficulty. However, it should be recognized that these suboptimal trades will likely reduce the overall trade potential that could occur in an unrestricted water market. For example, an additional consideration is water quality. It may be necessary for a receiving mine to treat water and this cost would need to be subtracted from the new regional total water productivity. Alternatively, consideration of dilution potential on a receiving site could be added as a factor in the propensity to trade matrix and thereby potentially change the order of water trades while maintaining a region's improved total water productivity overall.

Conclusion

This paper has demonstrated a new method to assess the potential for water trading between a group of mines (or other water users) within a given region, thereby increasing regional total water productivity. The method is based on the statistical water balance of each site and calculation of the propensity for mines to trade water among sites. For a demonstration region, in which 16 coal mines were considered, there was an unmet need for 11,440 ML of water that could not be met by trading and 340 ML that could be traded/exchanged. The direct monetary value of this saved water could add significant revenue/margin and improve the regional water productivity ratio of coal production. Other uses of this water may have considerable indirect monetary value to surrounding communities that may impact the mining industry's social license-to-operate over the long term. The ultimate value to the industry of water trading outside the mining sector may, in the long term, far outweigh the direct monetary value of the water itself if it influences mining's social license-to-operate under conditions where water security is threatened by decreasing availability and increasing competition. To further develop the concept of cross-sector water trading and assess the costs, benefits, risks, and opportunities of such a scheme will require a more extensive test case of these methods. This approach provides a more complete sustainable development view of the value of water within mining regions in Australia than was previously available.

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