THE ROYAL SOCIETY

Land cover change and water vapour flows: learning from Australia

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Australia is faced with large-scale dryland salinization problems, largely as a consequence of the clearing of native vegetation for cropland and grassland. We estimate the change in continental water vapour flow (evapotranspiration) of Australia during the past 200 years. During this period there has been a substantial decrease in woody vegetation and a corresponding increase in croplands and grasslands. The shift in land use has caused a *ca.* 10% decrease in water vapour flows from the continent. This reduction corresponds to an annual freshwater flow of almost 340 km^3. The society-induced alteration of freshwater flows is estimated at more than 15 times the volume of run-off freshwater that is diverted and actively managed in the Australian society. These substantial water vapour flow alterations were previously not addressed in water management but are now causing serious impacts on the Australian society and local economies. Global and continental freshwater assessments and policy often neglects the interplay between freshwater flows and landscape dynamics. Freshwater issues on both regional and global levels must be rethought and the interplay between terrestrial ecosystems and freshwater better incorporated in freshwater and ecosystem management.

Keywords: freshwater; terrestrial ecosystems; evapotranspiration; land cover change; salinization; Australia

1. INTRODUCTION

Australia is the driest inhabited continent on earth (in terms of run-off per unit area; McMahon *et al.* 1992). Freshwater scarcity in developed areas is increasing due to withdrawal of water from rivers and aquifers for irrigation, industry and household use. In addition to freshwater scarcity, the continent is facing another challenge of huge ecological and economic dimensions. The challenge refers to too much water in the soils manifested as large-scale dryland salinization, with substantial costs for the Australian society. Production loss due to saline river water, health hazards, deterioration of agricultural lands, destruction of infrastructure in rural and urban areas (NLWRA 2001), and loss of biodiversity and ecosystem services in both terrestrial and aquatic environments are among the social costs (MDBC 1999*b*).

In the early twentieth century the link between the clearing of land and salinization of soil and surface water was addressed (Wood 1924). Despite this, land clearing of native vegetation has continued in Australia. The replacement of native woody vegetation with annual crops and grasses has changed the hydrology of the continent (McFarlane *et al.* 1992; McMahon *et al.* 1992). It is well known that changes in terrestrial ecosystems such as deforestation and afforestation can alter water partitioning and thus the proportion of rainfall that is diverted into run-off (liquid water flows) or evapotranspiration (water vapour flows) (Calder 1999). In general, liquid water flows increase with deforestation and decrease with afforestation (Bosch & Hewlett 1982; Bruijnzeel 1990; Sahin & Hall 1996) and several estimates are available at the scales of drainage basins (Bosch & Hewlett 1982; Vertessy 1999; Zang *et al.* 1999). The response to treatment is, however, highly variable and for the most part unpredictable and the effects depend on the intensity and manner in which the clearance is carried out (McCulloch & Robinson 1993).

Trees coevolve with light and water content in the soil to yield maximum productivity of tree foliage (Eagleson 2002). The woody native vegetation in Australia has evolved to cope with the dry Australian preconditions and returns most of the rain to the atmosphere as vapour water, minimizing the amount of run-off and groundwater recharge of liquid water (Hatton & Nulsen 1999). The clearing of woody vegetation in Australia has fundamentally altered the intimate interplay of terrestrial ecosystems and the hydrological cycle. Too much water has become a serious problem on the dry Australian continent.

It is an intriguing dilemma, with a continent that is both dry and wet at the same time. To our knowledge the scale of freshwater redirection from vapour to liquid has not yet been quantified, and such issues are not part of the national water accounting. In this article, we make a first approximation of the magnitude of hydrological alterations caused by land cover changes on the Australian continent. By comparing vegetation distribution in 1780 and in 1980 we estimate the change of water vapour flows

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in Australia caused by large-scale clearing of vegetation in the past 200 years. The purpose is to get a sense of the scale of alterations of water vapour flows caused by land cover change in order to unravel whether or not this is of importance in a broader context. It is not our intention to scrutinize the total freshwater situation in Australia.

The first part of the paper deals with the approach and methods used for assessing the changes in water vapour flows from land cover change. The results of the estimates are presented in § 2, followed by their implications for combined terrestrial and freshwater management in Australia. There might be several lessons of the Australian case to be learned for other countries, especially in the tropics and subtropics, where there is rapid human-induced change of ecosystem structures, processes and resilience. The findings are therefore discussed in the context of global freshwater assessments. We plea for a broader perspective to incorporate the role of freshwater in the capacity of continental ecosystems to generate and sustain ecosystem services on which social and economic development ultimately depends.

2. CHANGES IN WATER VAPOUR FLOWS IN AUSTRALIA 1780–1980

(a) *Vegetation change*

It has been suggested that demand for cropping areas was the primary cause for the clearing of woody vegetation until the 1950s. Grazing that caused further clearing has since then increased in importance, and some data indicate a peak in clearing rates in the 1970s (Graetz 1998). The European settlers in the late eighteenth century brought agricultural practices that were developed in a very different hydroclimate to a continent with older, drier and relatively nutritionally poor soils, lower hydraulic gradients, and higher climatic and hydrologic variability. In contrast to woody vegetation, annual crops and grasslands transpire water only during part of the year and have shallow rooting structures. They do not capture as much rainfall and soil moisture as the native vegetation (Hatton & Nulsen 1999). Less precipitation is returned to the atmosphere as water vapour and thus more water is draining through the soils leading to rising water tables (figure 1).

The Australian soils are saline. The increased water movement through the soils mobilizes salts. This causes problems with salinity both in rivers (i.e. river salinity) and at, or close to, the soil surface and the growth of most plants is severely reduced (referred to as dryland salinity) (MDBC 1999*b*). Recent estimates indicate that *ca.* 5.7 million hectares are currently at risk of dryland salinity, which could rise to over 17 million hectares by 2050. Western Australia is the worst off with 33% of the land area at risk of salinization, followed by Victoria (NLRWA 2001).

We based our estimate of vegetation change on digitalized versions of the Carnahan 1780s and 1980s vegetation maps (Carnahan 1990) to get the aerial extent of different vegetation classes. The Carnahan vegetation maps are the only available data on terrestrial vegetation types in Australia that are consistent across the continent and available for both present and pre-European vegetation. These maps are compiled at a coarse scale (1 : 5 million) and provide a reliable but very broad overview of the distribution of major vegetation types. A National Vegetation Information System, which will be more detailed, is under development by the National Land and Water Resources Audit in Australia. More detailed data of today's land use exists for forests (NFI 1997) and for some other kinds of land use (Dunlop *et al.* 1999). If we were to use more developed data we would however have had to use different maps for different vegetation classes. We used the Carnahan maps consistently to avoid double counting and the uncertainty that relates to overlaps.

The vegetation cover in the Carnahan vegetation classes was defined in terms of its growth form, foliage cover and, in most cases, predominant plant genus. Croplands were reported as grasslands on the Carnahan maps (Carnahan 1990). We therefore used crop data from the ABS (unpublished data), and subtracted the croplands from the grassland vegetation class (table 1).

We regrouped the Carnahan vegetation classes into six new subgroups (wet dense forest, open forest, woodland, wet grassland, grassland and croplands (21 crop subclasses)) (table 1). The main parameter for regrouping was extent of tree cover as it is an important factor influencing the annual water vapour flow from a system. The height and density of the tallest vegetation cover differentiate the vegetation classes (Carnahan 1990). Only areas sown and harvested are included in the cropland subclass. Pasture that is grazed but not harvested was estimated as grassland and not cropland. Inland water bodies, littoral zones and urban areas are not accounted for in this study.

The digital vegetation maps were overlaid by a map of SDs (Bureau of Rural Sciences, unpublished data) in a computer-based GIS system. In this way changes in total area of each vegetation class in each SD could be derived.

The decrease in area between 1780 and 1980 of the woody vegetation classes (wet dense forest, open forest, woodland) corresponds with the increase in grassland/croplands and is *ca.* 80×10^6 ha. Previously, it has been estimated that 12 to 20 billion trees were removed from the Murray–Darling basin alone (Hatton & Nulsen 1999), and that almost half of the woody vegetation has been cleared in the intensively used agricultural zone (Barson *et al.* 2000).

(b) *Estimating changes in water vapour flows from land cover change*

There are several ways of assessing water vapour flows from terrestrial areas. The most common way is through a water balance equation, where precipitation over land, and liquid run-off to rivers in a catchment are estimated. This is an indirect method where vapour flow is estimated as the amount of precipitation that does not reach the river. Several catchment water balance studies have used this approach (see Bosch & Hewlett 1982; Vertessy 1999; Zang *et al.* 1999).

Our assessment of changes in water vapour flows from forests, woodlands and grasslands during 200 years draws heavily on the methodology developed by Rockström *et al.* (1999). Their assessment, as well as this estimate, is based on literature reviews of annual water vapour flows

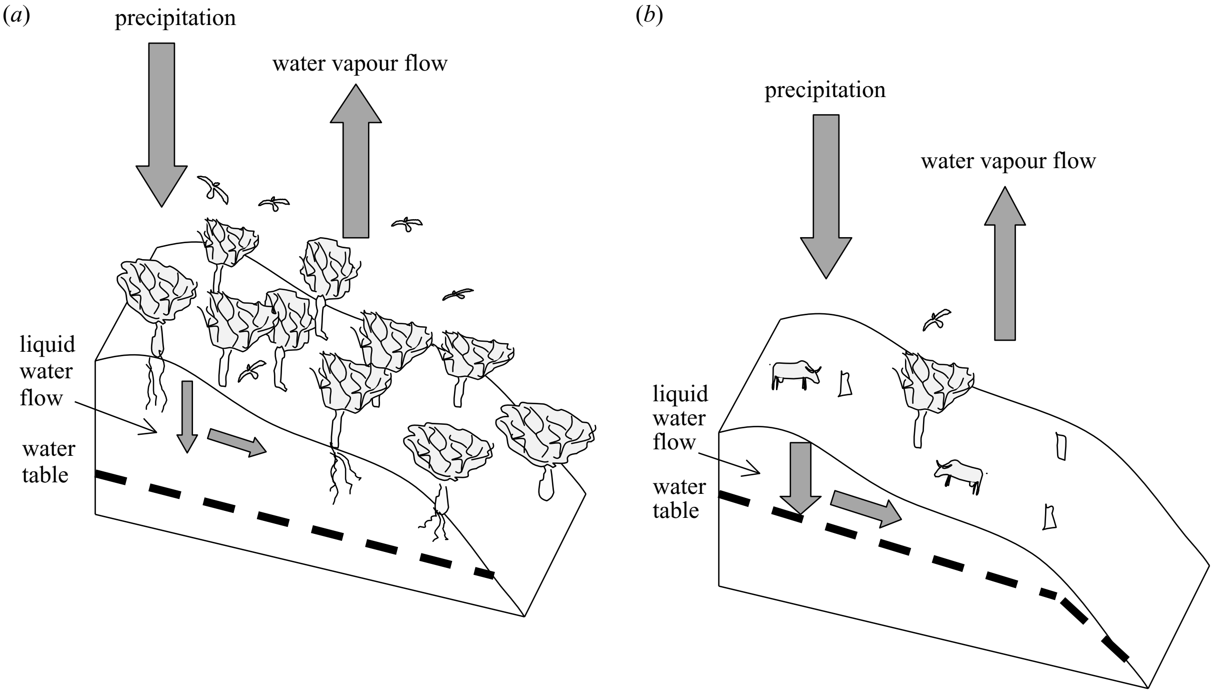

Figure 1. Clearing of deep-rooted perennial vegetation has altered freshwater flows in Australia. (*a*) Before clearing and (*b*) after clearing. Less freshwater is returned to the atmosphere as water vapour flow after clearing while more water runs off the land or drains into the groundwater tables as liquid water, which is illustrated by the change in the thickness of the arrows.

Table 1. The vegetation subgroups used in this study, reclassed after Carnahan vegetation classes, the areal extent of the vegetation types and the amount of change in the area 1780–1980.

vegetation type	Carnahan vegetation classes	area in 1780 ('000 ha)	area in 1980 ('000 ha)	change (%)
wet dense forest	T4+M4+L4	4567	3272	−28
open forest	T3+M3+L3	63296	34771	−45
woodland	M2+L2	155511	105544	−32
wet grasslands	G4[a]	1429	2127	49
grassland	M1+G3+F3+F4[b]	53875	95405	77
dry shrub and grassland	L1+S1+S2+Z1+Z2+Z3+H2+G1+G2+F1 +F2+S3	478567	493026	3
croplands[c]		0	21192	

[a] The area of sugarcane (ABS, unpublished data) has been subtracted.

[b] Area of croplands (ABS, unpublished data) have been subtracted, except for horticultural complexes as they were not included in the data from the Carnahan maps.

[c] Croplands were further subdivided into 21 subgroups (see table 3); data from ABS (2000).

(mm yr^{-1}) from major terrestrial ecosystems. A somewhat different method, described below, was used for croplands.

(c) *Forests, woodlands and grasslands*

We conducted a literature review of water vapour flows from Australian ecosystems. Where there was a lack of Australian data, we used data from sites with a similar hydroclimate (see table 2 for data and sites). The average water vapour flow of each study was registered and the average water vapour flow of all studies within a vegetation class calculated. The ranges of estimates in each subclass are based on the lowest and highest average water vapour flow from each study. This indicates that there are higher and lower values that can be found for each subclass. As the vegetation classes are very coarse they do not include variation such as density and composition of the lower strata within a subgroup and age of trees. Variation also existed in the methods, and precision of the methods, with which evapotranspiration was estimated in the literature.

As estimates for wet grasslands were not found in the literature, we assumed an annual mean water vapour flow of 800 mm with a range of between 600 and 1000 mm yr^{-1}. Table 2 shows the mean, minimum and maximum estimation for each vegetation type.

We multiplied the areas (km^2) of *forests, woodlands, grasslands* and *shrublands* from the Carnahan vegetation maps (Carnahan 1990) (table 1), with the mean annual water vapour flow (mm yr^{-1}) of each vegetation subclass (table 2):

$$\text{total water vapour flow } (\text{km}^3\ \text{yr}^{-1}) = \text{area } (\text{km}^2) \times \text{water vapour flow } (\text{mm yr}^{-1}).$$

Table 2. Water vapour flow for different vegetation covers.
(ET, the mean annual water vapour flow (mm yr^{-1}) of each study; P, the precipitation of the site of the estimate. The average value for each vegetation class is indicated in bold.)

	area in 1780 ('000 ha)	area in 1980 ('000 ha)	vegetation	location	P	ET	reference
wet dense forest	4567	3272	tropical rainforest	Western Java	2851	1481	Calder *et al.* (1986)
			rainforest/wet eucalyptus	Australia	1537	1159	Vertessy (1999)
			tropical rainforest	various		1376	Lesack (1993)
						1339	
open forest	63296	34771	forest	New South Wales	765	678	Vertessey & Bessard (1999)
			jarrah forest	Western Australia	880	931	Stoneman (1993)
			open forest	Victoria	1430	928	Feller (1981)
			mountain ash		1800	1060	Vertessey *et al.* (1998)
			river red gum	Western Australia	432	1148	Marshall *et al.* (1997)
			various		1290	952	Marshall *et al.* (1997)
			pine plantation		1250	978	Cornish (1989)
average						**953**	
woodland	155511	105544	savannah	various		870	L'vovich (1979)
			open eucalyptus woodland	Northern Territory	1720	1110	Cook *et al.* (1998)
			savannah	various		894	Frank & Inouye (1994)
			woodland	New South Wales	858	666	Vertessey & Bessard (1999)
average						**885**	
grasslands	53876	95405	grasslands	New South Wales	691	603	Vertessey & Bessard (1999)
			grasslands/pastures	southeastern Australia	710	582	Vertessy 1999
			grasslands	Australia	677	607	Zhang *et al.* (1999)
			annual pasture and crops	Western Australia	694	378	Scott & Sudmeyer (1993)
			pasture	Western Australia	800	390	Greenwood *et al.* (1985)
average						**512**	

(d) *Dry grass and shrublands*

There was a general lack of data for dry grasslands and shrublands. These occur mainly in areas with precipitation of less than 500 mm yr^{-1} (Parkinson 1986; Carnahan 1990). On a large spatial scale, in low rainfall zones almost all precipitation returns to the atmosphere as water vapour (Le Houerou 1984). We used precipitation as an approximation for water vapour flows from this vegetation subclass:

$$\text{total water vapour flow } (\text{km}^3\ \text{yr}^{-1}) = \text{area } (\text{km}^2) \times \text{precipitation } (\text{mm yr}^{-1}).$$

Total precipitation in each SD was estimated from the *Atlas of Australian Resources* (Parkinson 1986) map of isohyets, overlaid by a map of SDs. The area between each pair of isohyets in each SD was estimated and multiplied by the average of the two isohyets defining the area. The total annual precipitation in Australia was estimated to be 3314 $\text{km}^3\ \text{yr}^{-1}$, equivalent to an average of 431 mm. This corresponds well with previous estimates of total precipitation from, for example, L'vovich (1979) who reports an annual average precipitation of 3390 $\text{km}^3\ \text{yr}^{-1}$.

(e) *Croplands*

A different method was used in croplands. The various crops were divided into 21 subclasses (table 3). Biomass production in croplands is roughly linearly proportional to the water vapour flow, for constant hydroclimatic conditions when water is not limiting growth (Sinclair *et al.* 1984). The slope of the relationship between biomass growth and water vapour flow is defined as the water use efficiency or WUE. We have used these relationships in the estimation of water vapour flows from croplands, by multiplying the annual crop production (t yr^{-1} of harvested economic biomass) with WUE estimates ($\text{m}^3\ \text{t}^{-1}$). The total water vapour flows for each crop subclass was estimated as

$$\text{total water vapour } (\text{m}^3\ \text{yr}^{-1}) = \text{yield } (\text{t yr}^{-1}) \times \text{WUE } (\text{m}^3\ \text{t}^{-1}).$$

For each subclass, estimates of WUE were gathered from published literature. WUE data from several research sites were included for each major crop and subclass in order to reflect the variability in water vapour flow for different agricultural settings. Mainly Australian data were used. This method is the same as used by Postel (1998) and Rockström *et al.* (1999). This is a more valid method for estimating water vapour flows from croplands because there are more accurate estimates of WUE ($\text{m}^3\ \text{t}^{-1}$), i.e. the amount of water (m^3) used by plants per unit biomass (t), than of water vapour flow (mm ha^{-1}). It is also a more suitable method for croplands as they vary substantially in intensity of production.

We used data on average annual production from 1986 to 1996 (ABS, unpublished data). The time-span was used to minimize the effect of inter-annual yield variations.

3. RESULTS

The water vapour flow through Australian ecosystems has decreased substantially with the clearing of land during the past 200 years. The decrease in area of woody vegetation has led to a corresponding increase of grasslands and shrublands. The annual mean water vapour flows from woody vegetation (wet dense forests, open forests and woodlands) was 2040 km^3 in 1780 and 1310 km^3 in 1980 and has thus dropped by *ca.* 730 km^3. Meanwhile the increase from grasslands, shrublands and croplands is estimated to be only 390 km^3 (from *ca.* 1400 km^3 in 1780 to almost 1790 km^3 in 1980) (see table 4). What is a zero-sum game when it comes to land-use change is not a zero-sum game when it comes to water use. The visible land-use change has caused large-scale hydrological changes on the continent: changes that have not been accounted for in conventional water assessments.

The total water vapour flow from the Australian continent has decreased by something like 10% in the past 200 years, based on the mean values of 1780 and 1980. In the 1780s the estimated water vapour flow was 3440 $\text{km}^3\ \text{yr}^{-1}$ (range of 2380–3760 $\text{km}^3\ \text{yr}^{-1}$), in the 1980s the flow was 3100 $\text{km}^3\ \text{yr}^{-1}$ (range of 2620–4190 $\text{km}^3\ \text{yr}^{-1}$). Contemporary (1980s) flows correspond well with earlier estimates from the 1970s by the Russian hydrologist L'vovich amounting to 3028 $\text{km}^3\ \text{yr}^{-1}$ (L'vovich 1979). His estimate was, however, based on data on precipitation and run-off. The total decrease in annual water vapour flow is thus *ca.* 340 km^3.

As the vegetation classes are very coarse they do not take into account within-class variation such as density and composition of the lower strata within a subgroup, age of trees, and within-class variation in hydroclimates. This variation adds to the wide range in the water vapour flow results. Variation also existed in the methods, with which evapotranspiration was estimated in the literature. The estimated vegetation alteration captures water vapour changes that are primarily due to land-cover conversion.

Substantial land-cover modification has been ongoing in Australia for the past 200 years, where less visible within-class modification has occurred (Carnahan 1990). Such modifications include thinning of lower vegetation strata, change of forest age and changed fire and grazing regimes; changes to water vapour flows from these vegetation changes are not estimated in this study. These modifications represent structural modifications that change ecological processes, even though they are seldom captured in assessments of land-cover changes (for a discussion about the Amazon see Nepstad *et al.* (1999)).

Australia's large and rapidly expanding area affected by dryland salinization seems to be driven by the reduction of terrestrial water vapour flow, which has led to a rise in water tables. As such, spatially explicit estimates of change in water vapour flows may be used to predict future rates of dryland salinity. We have, however, not quantified how much of the decrease in water vapour flow translates to rising water tables.

Land-cover changes can also affect rainfall. Regional rainfall reductions have been observed in the Sahel as the result of reductions in water vapour flow from vegetation, moisture flux convergence and increased subsistence and shifts in the summer monsoon belt (Xue & Shukla 1993; Savenije 1996). Changes in albedo can also influence precipitation, as has been the case in the Mediterranean due to overgrazing (Chapin *et al.* 1997).

Table 3. Classification of crops, data on production and WUE for different vegetation covers.

crops	production ('000 t)[a]	WUE (m^3 t)	references
pasture for hay	8370	694	Doorenbos & Kassam (1979); Heichel (1983); Waldren (1983); Shih & Snyder (1985); Bolger & Matches (1990); Power (1991); Armstrong *et al.* (1994); Johnsson (1994); Oliva *et al.* (1994) and Thomas (1994)
cereal crops for hay	867	411	Beech & Leach (1989); Armstrong *et al.* (1994) and Mahalakshmi *et al.* (1994)
wheat	14477	1736	Gregory (1988) and Beech & Leach (1989)
oats	1586	1368	Scott & Sudmeyer (1993)
barley	4160	1348	Gregory (1988); Scott & Sudmeyer (1993) and Mahalakshmi *et al.* (1994)
sorghum	1256	1204	Doorenbos & Kassam (1979); Turner & McCauley (1983) and Rockström (1992)
rice	806	1099	Doorenbos & Kassam (1979); Shih *et al.* (1983); Turner & McCauley (1983) and Rockström (1992)
cotton seed	781	2083	Doorenbos & Kassam (1979)
cotton raw	287	5454	Grimes *et al.* (1969); Hearn (1980) and Lascano *et al.* (1994)
lupins	868	2424	based on data for pulses
sugarcane	26726	123	Doorenbos & Kassam (1979); Gascho & Shih (1983) and Yates & Taylor (1986)
oilseeds[b]	1365	3083	Doorenbos & Kassam (1979)
pulses[b,c]	2205	2424	Doorenbos & Kassam (1979); Ashley (1983); Boote (1983); Rockström (1992) and Barros & Hanks (1993)
maize[b]	270	1151	Hillel &Guron (1973); Stewart *et al.* (1975); Doorenbos & Kassam (1979) and Rockström (1992)
triticale[b]	383	1517	based on the data for wheat, oats and barley
vegetables	405	135	Doorenbos & Kassam (1979); Pruitt *et al.* (1984) and Shih & Rahi (1984)
citrus fruit	508	350	Doorenbos & Kassam (1979)
bananas	176	276	Doorenbos & Kassam (1979)
grapes	896	375	Doorenbos & Kassam (1979)
other fruit	452	265	Doorenbos & Kassam (1979)
nuts	18	415	Kanber *et al.* (1993)

[a] From ABS (unpublished data).
[b] From ABARE (1999); includes years 1992–1993 to 1996–1997.
[c] Excluding lupins.

Table 4. Total water vapour flow ($km^3\ yr^{-1}$) from different vegetation types in Australia in 1980 and 1780.

		wet dense forest	open forest	woodland	wet grassland	grassland/ pasture	dry shrubland and grassland	cropland	total
1980	mean	44	332	934	17	488	1226	56	3097
	min[a]	38	236	703	13	361	981[b]	45[b]	2375
	max[c]	49	399	1172	21	579	1471	68	3758
1780	mean	61	603	1376	11	276	1108	0	3436
	min	53	429	1035	9	204	886	0	2616
	max	68	727	1726	14	327	1330	0	4191

[a] Min is the lowest average estimate found in the literature (i.e. if several estimates are given in a certain reference, their average is noted. The lowest average found is reflected by the min estimation).
[b] Min/max for dry shrublands and grasslands, and croplands is estimated on a qualified assumption that this varies with 20%.
[c] Max is the highest average estimate found in the literature.

In this study, water vapour flows were found to have decreased between 1780 and 1980. It was, however, not estimated how much of this decrease has resulted in water table rise. The full difference in water vapour flows between the 1780s and 1980s cannot be attributed to increase in groundwater recharge and river flows as precipitation might have been altered.

The change in water vapour flow is almost as large as the annual continental liquid water flow of 362 $km^3\ yr^{-1}$ as estimated in the late 1960s (L'vovich 1979). It does not seem possible that continental run-off would have been almost non-existent 200 years ago. However, it has been suggested in the literature that liquid water run-off would have been close to zero for non-cleared southern Australian ecosystems (Hatton & Nulsen 1999). The large inter-annual variability of rainfall and the buffered flows in all river systems could have insured that rivers and streams maintained flow regimes.

4. POLICY IMPLICATIONS

Numerous small-scale decisions, rational within a certain institutional and cultural context, on the management of the landscape have been made during the past 200 years without a deeper recognition of the long-term societal costs of altered freshwater flows. Segregated management of freshwater from terrestrial ecosystems, including agriculture, has been a management strategy successful in the short term that has caused severe long-term social, economic and ecological costs to society. Short-term success is often gained at the expense of long-term, large-scale sustainability (Holling & Meffe 1995; Redman 1999) and Australia is just one example of widespread ecological and hydrological blindness (van der Leeuw 1998; Folke *et al.* 2002).

(a) *A need for a broader perspective on freshwater*

Australia is a dry continent, where water scarcity in developed areas is increasing due to withdrawal of water from rivers and aquifers for irrigation, industry and households. In for example the Murray-Darling, the largest river system on the continent, the fact that the river is getting depleted is reflected in a drop of the mean annual flow of some 79% (MDBC 1995). Several solutions to water scarcity have been tried. In 1996 a 'cap', or moratorium, on freshwater withdrawal was initiated in order to secure the health of aquatic ecosystems and to increase efficiency of water distribution in society. Water trading is also under development to encourage increase in water-use efficiency (MDBC 1999*a*). The focus of water assessments in Australia has until recently been on the management and allocation of 20 $\text{km}^3\,\text{yr}^{-1}$ of liquid water (AATSE 1999). At the same time the total Australian continental water account has changed by *ca.* 340 $\text{km}^3\,\text{yr}^{-1}$ owing to land-cover conversions.

The estimate in this paper is rough and static, but highlights an important aspect in water assessments and accounting. The real society-induced change of water flows in the landscape as a consequence of land-cover change, are more than 15 times greater than the volume of diverted water for household, industry and irrigation. It is the latter that has been in focus and caused much debate and controversy in the Australian society. Although that carries significant issues for society, we argue that the scope of freshwater management has to be broadened. The results clearly illuminate the strong interplay between the hydrologic cycle and terrestrial ecosystem processes that modify and redirect freshwater flows. This highlights the need of an intentional management of the whole landscape in a catchment-based approach. These are insights that are rapidly developing, out of necessity, in Australia.

(b) *No easy solutions to the Australian crisis*

In water policy, irrigation for agriculture is recognized as the largest user of freshwater (see figure 2*a*). The main starting point in the literature on future demands for increased food production to a growing world population is that more water is required (Postel 1998; Rockström *et al.* 1999). From a total water balance perspective the agricultural systems common in Australia use too little soil water compared with natural vegetation, and thus contribute to dryland and river salinity. There is a growing awareness of the role of rain-fed agriculture in global food supply (Rockström & Falkenmark 2000), although irrigated land still is the focus for much of the investments to increase food production.

There is a call to restore the hydrological functions of the native terrestrial ecosystems at both local and regional scales in Australia (Hatton & Nulsen 1999). Many analyses suggests that this can only be done with the revegetation of trees or other perennial plants in substantial fractions of cleared parts of the catchments (Hatton & Nulsen 1999), and this has to be socially acceptable. Effort goes into understanding how to do this while still maintaining economic returns from the landscape. The transition to a transport system based on methanol derived from woody biomass is one option being tested, which would require 25 million hectares of biomass plantation by the year 2050 (Foran & Crane 2000). It has been estimated on a global level that large-scale bioenergy production could appropriate as much water vapour flow as today's croplands (Berndes 2002).

Large-scale afforestation requires careful analyses of other potential trade-offs. One example refers to liquid water availability. According to our estimate, it is likely that more water reaches rivers and aquifers today than 200 years ago. However, society has increased its dependence on, and appropriation of, this flow of water. Attempting to restore the hydrological functions of the 1780s vegetation can result in less water for downstream water users as well as higher river salinity levels (Vertessy & Bessard 1999).

Restoring the landscape involves managing the terrestrial ecosystems for more than one product and farming systems in general generate various ecosystem services (Björklund *et al.* 1999). Maintaining the water balance of the landscape can be seen as a fundamental ecosystem service and the development of tradable salinity credits is one way of giving this service a market value.

An Australian project has been initiated called 'the nature and value of Australia's ecosystem services', coordinated by CSIRO Sustainable Ecosystems in order to highlight the multi-functionality of the Australian ecosystems (Walker 2000). Hopefully this project can help in finding alternative farming practices that generate services as well as products. In this context it becomes counter-productive to separate the management of freshwater flows and of ecosystem goods and services whether in terrestrial or aquatic ecosystems. Effective water management has to include an understanding of the capacity of terrestrial ecosystems to influence the size, timing and pathways of water flows, and the processes behind this capacity.

Securing ecosystem capacity involves a dynamic understanding. The Australian landscapes are subjected to frequent disturbances such as fire and grazing. Such ecosystem disturbances can influence vapour and liquid water flows. One example includes water vapour flow decrease and liquid water flows increase directly after a disturbance on forest cover (e.g. clearing, fire, insect outbreak), a trend that reverses during regrowth (Bosch & Hewlett 1982). Another example is changes in infiltration capacity that alter local water balances due to altered grazing regimes (Walker 1993). This highlights the need for not only static estimates of water vapour changes, but also

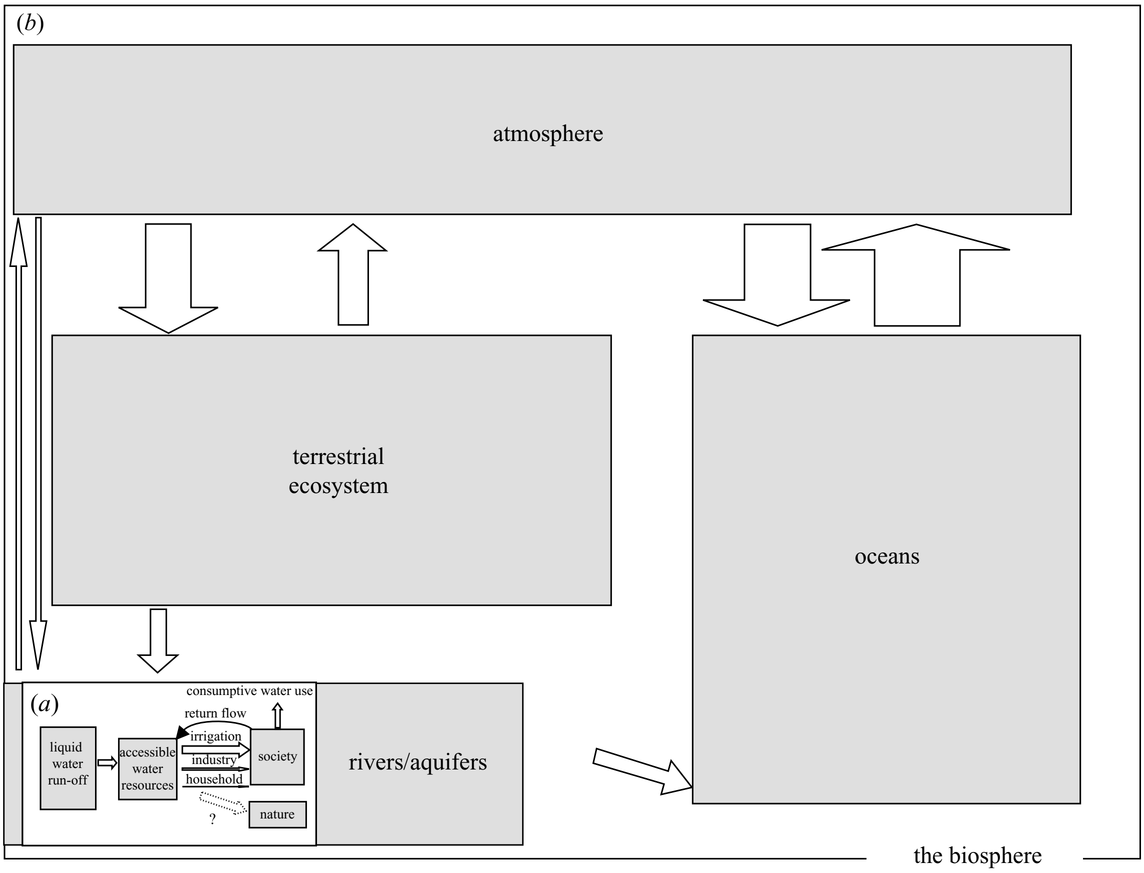

Figure 2. (*a*) The mental perception of fresh water as a finite input for societal production. Roughly 30% of the annual liquid water run-off is estimated as accessible for societal production, 20–30% of this is withdrawn for use in society and out of this, 65–70% goes to irrigation, 20–25% to industry and 5–10% to households. The amount of withdrawn fresh water that evaporates is called consumptive water use and is seen as an irretrievable water loss. Some freshwater is returned to rivers and aquifers. In the past decades nature has begun to be seen as a legitimate stakeholder. (*b*) Freshwater as the bloodstream of the biosphere. The perception of water described in (*a*) only sees fresh water in the river/aquifer sub-system. However, humans also change large-scale processes in other sub-systems (e.g. terrestrial ecosystems, the atmosphere and rivers), which alters freshwater flows. Human society is seen here as an integral part of nature that depends on the capacity of ecosystems to sustain society with goods and services.

a more dynamic understanding of the interactions of terrestrial ecosystems and freshwater flows. It includes the role of building ecological resilience in the landscape while restoring the hydrological functions (Carpenter *et al.* 2001).

5. IMPLICATIONS FOR FRESHWATER ASSESSMENTS

It is often argued that it is not until there is a crisis that broader perspectives are developed (Gunderson *et al.* 1995). In Australia, dryland salinization constitutes a major crisis that might trigger a change in the perception of freshwater in management, policy and research. Hopefully this can also be a lesson for the rest of the world, especially in the arid and semi-arid tropics.

Freshwater assessments on global and continental scales have primarily focused on the amount of available liquid water in rivers and aquifers (Gleick 1993; Shiklomanov 2000), neglecting the vast amount of freshwater flowing through terrestrial ecosystems. It is not fully appreciated that land-use changes redirect freshwater flows and that human appropriation of freshwater flows alter terrestrial ecosystem dynamics. The results argue for a change in the perception of freshwater, from primarily an input to societal production, to recognition of its role as the bloodstream of the biosphere (Falkenmark 2000).

(a) *Continental assessments of freshwater primarily relate to liquid water resources*

Generally it is the annually renewable liquid water that is recognized as a freshwater resource. Liquid water flows (or ‘blue water’ (FAO 1996)) consist mainly of (i) regional run-off, (ii) inflow of groundwater into river networks, and (iii) yearly renewable upper groundwater that is not drained by rivers (Shiklomanov 2000). The global water assessments indicate an annual liquid freshwater resource of *ca.* 40 000 $\text{km}^3\,\text{yr}^{-1}$ (L’vovich 1979; Shiklomanov 2000) of which *ca.* 30% is accessible to humans (Postel *et al.* 1996). The amount of water withdrawn is estimated to be *ca.* 3800 $\text{km}^3\,\text{yr}^{-1}$ and is expected to rise to 5200 $\text{km}^3\,\text{yr}^{-1}$ in 2025 (Shiklomanov 2000). Irrigation accounts for an estimated 65–70% of the total liquid water withdrawals. Of the used liquid water 2000 $\text{km}^3\,\text{yr}^{-1}$ is consumptive water use, i.e. withdrawn water that evaporates and that here is looked upon as irretrievable freshwater loss (Shiklomanov 2000).

In Australia the liquid water availability has been estimated to 362 $\text{km}^3\,\text{yr}^{-1}$ (L'vovich 1979) of which 102 $\text{km}^3\,\text{yr}^{-1}$ (or 28%) has been suggested as economically feasible to appropriate (AATSE 1999). Of the 69 $\text{km}^3\,\text{yr}^{-1}$ of liquid water extracted from groundwater and rivers at present, 49 $\text{km}^3\,\text{yr}^{-1}$ is returned as regulated discharge (ABS 2000) and *ca*. 20 $\text{km}^3\,\text{yr}^{-1}$ is used in various sectors in society (AATSE 1999; ABS 2000). The amount of withdrawn water has risen quickly during the last decades (AATSE 1999; ABS 2000). Agriculture is the largest sector using *ca*. 70% of the appropriated water, households being the second largest sector with 8% of net liquid water withdrawals (ABS 2000).

In these global and continental water assessments, irrigated agriculture, industry and households are acknowledged as the dominant water-using sectors. In the last decade 'the environment' (mainly aquatic ecosystems) has entered the discussions as a legitimate water-using sector, which generates aquatic ecosystem services (Postel & Carpenter 1997). This has given rise to discussions at local and global levels on how much water will be needed to sustain the aquatic ecosystems of rivers, lakes, wetlands and estuaries, but without fully recognizing the role of terrestrial ecosystems in the hydrological cycle.

Hence, assessments of freshwater availability and use predominately focus on the visible liquid water available in rivers and aquifers. Water is treated as an input to societal production, with the various water users (including the aquatic environment) competing for a finite available volume of freshwater (figure 2*a*).

(b) *Global change and water vapour flows*

Ecosystems have been modified by human societies throughout human history (Grimm *et al.* 2000; McIntosh *et al.* 2000), but never before over such large scales and at such fast rates. This has resulted in a growing concern about the eroded capacity of ecosystems to support a society with goods and services essential for human well being (Folke 1991; Jansson *et al.* 1994; Daily 1997). The capacity of continental ecosystems to generate and sustain ecosystem services is intimately coupled with the availability of freshwater (Rockström *et al.* 1999).

The numbers often referred to in freshwater assessments do not include the large changes in terrestrial water use as a result of human alterations of vegetation. There have been a couple of attempts to analyse human impacts in terrestrial ecosystems on a global scale in relation to freshwater flows. L'vovich & White (1990) estimated in a first, tentative approximation, that evapotranspiration rates would have been 6540 $\text{km}^3\,\text{yr}^{-1}$ higher when these areas were covered by natural vegetation. They also estimated that water vapour flows have increased by 2470 $\text{km}^3\,\text{yr}^{-1}$ due to irrigation. The total water vapour flow would thus have decreased by 4070 $\text{km}^3\,\text{yr}^{-1}$ (6%) on a global scale. Postel *et al.* (1996) estimated that humanity now uses 26% of the total continental water vapour for appropriation of net primary production. Rockström *et al.* (1999) estimated the global water vapour flow from ecosystems that generate most of the ecosystem services to be 63 000 $\text{km}^3\,\text{yr}^{-1}$. More generally, analyses by the International Geosphere–Biosphere Programme couple vegetation distribution, climate and water flows to acknowledge the role of vegetation for water flows and climatic factors (Hutjes *et al.* 1998). These studies present a new perspective on water, highlighting its role as the bloodstream of the biosphere (figure 2*b*).

6. CONCLUSIONS

Freshwater has in the past mainly been perceived as an input factor for societal production. It is, however, the bloodstream of the biosphere and sustains a flow of ecosystem goods and services that society depends upon. Likewise, terrestrial ecosystems are needed to sustain the timing, composition and pathways of water flows on which society depends. Assessments of global and continental water resources generally ignore this intimate interplay between terrestrial ecosystem processes and freshwater flows (Gleick 1993; Shiklomanov 2000). It is indeed a major fallacy of most freshwater arithmetic that large-scale changes in ecosystem processes affecting water flows are not included in the assessment of freshwater availability and use.

Human dependence on the interplay of freshwater and terrestrial ecosystem processes needs to be clarified. Humans are part of nature and depend on its capacity to generate goods and services. This study indicates that the terrestrial support capacity for societal development in Australia has been reduced through changes in vegetation cover. A successful restoration requires ecological as well as hydrological knowledge and understanding, but it also has to be socially acceptable. Furthermore, it requires incentives and institutions with the capacity to respond to change in complex, dynamic and linked social-ecological systems (Berkes *et al.* 2003).

This is an enormous challenge for the Australian society with several lessons to be learned for the international freshwater community, especially in the tropics and subtropics, where there are rapid human-induced changes of ecosystem structures, processes and resilience. Global and regional assessments of freshwater flows and human water use tend to neglect the impact of human alterations of terrestrial ecosystems (Gordon & Folke 2000). In 'the Antropocene', on a human-dominated planet, we believe that these alterations are far too large to be neglected and leaving them out will not show the proper extent of the freshwater crises now being addressed at an international agenda.

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GLOSSARY

ABS: Australian Bureau of Statistics
GIS: geographical information system
SD: statistical division
WUE: water use efficiency