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Review Article

Inter-Related Hydrologic Threats to Australia's Agricultural Potential

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Abstract

For the dry Australian continent agricultural activity is concentrated in the more humid perimeter. In these areas in particular, land clearing and agricultural development has initiated higher infiltration and groundwater recharge, reflected in the emergence of land degradation problems of salinization of low-lying landscape and acidification of soils. The accelerated use of groundwater for irrigation has brought concerns about the sustainability of that resource along with changed composition of groundwater derived from nitrate leaching from the soil, which restricts its use for drinking and contaminates streams. Each of these problems is worsening and contributing to reduced agricultural production and the potential availability of the groundwater resource. All these problems are induced by the common factor of changes in the groundwater hydrology. Recommendations are made on the need for integration of research, monitoring and management.

Keywords: Groundwater; Rainfall; Agriculture

Introduction

Australia is a dry continent where over 60% in area can be classed as semi-arid to arid; the exception is the perimeter of the country where the rainfall is higher and as a consequence is where the bulk of the population, now over 25 million and agriculture area concentrated (See figure 1). Furthermore, the population and agriculture have grown progressively since Europeans began to settle in the late 18th century. Agriculture has spread out from first settlements over the past two centuries and is now very important to the Australian economy, made-up with a diverse range of crop and livestock products of which 70% is exported.

Nonetheless agricultural progress has brought with it signs of degradation of the natural resources. Historically investigations of each of these problem areas were identified at different times. Probably, to generalize, the order in which the problems gained significance are: groundwater resource sustainability, salinization, nitrification and nitrate-rich groundwater and nitrification and soil acidification. More recently each of these problem areas was addressed together in nation-wide audits [11,12,28]. Two papers are especially important by demonstrating the interrelationship between salinisation and soil acidification [26,27], and recognising that "Australian agricultural systems have tended to substantially increase the amount of water draining below the plant root zone and entering the groundwater systems, compared to pre-European landscapes".

In this review article each of these interrelated problem areas is discussed, covering the basic cause and the role of water movement, the scale of the problem, amelioration measures, and brief comment on history including some critical political aspects, being aware that Australia is a Federation, with each State having specific responsibilities.

Figure 1: Generalized map of agriculture in Australia (modified from DAWR).

Cause of problems

To establish agriculture the clearing of deep-rooted trees and replacement by pastures and crops meant that less water was transpired by plants and recharge to the water table increased. The introduction of irrigation schemes had a similar effect causing salinization. The introduction of clover pastures and nitrogen and phosphorus fertilizers led to pollution of groundwater, the build-up in the organic matter of soil, nitrate leaching and product removal led to acidification of the soil, and tapping of deeper aquifers, especially from large yielding bores for irrigation led to a drop in groundwater storage and the risk of overdraft.

Before Europeans came to Australia the indigenous people lived in tribes as hunter gathers, with little disturbance to the hydrologic cycle. The groundwater system was considered to be in steady state with groundwater recharge being balanced by groundwater discharge. With the arrival of Europeans agricultural practice embarked on progressive clearing of native vegetation, which included deep rooted trees. More than a century later irrigation networks began to be constructed. These activities impacted on the hydrologic cycle by increasing the flux: fundamentally for the subsurface affecting two zones: the unsaturated zone, above the water table, where the pores are partially filled with water, and the saturated zone, below the water table, where the pores are filled with water. Within the saturated zone there existed steady--state flow, originating from recharge areas, where the flow is downward, leading to discharge areas, where the groundwater flow is upward. The groundwater recharge is from infiltrating rainfall via a moisture front and macropores in the unsaturated zone. Agriculture was just one of many human activities that disrupted the steady-state flow of the saturated zone. The hydrogeology of Australia is complex, although characterised by large sedimentary basins [1-5].

Referring to figure 2 the rainfall, which drives the hydrologic cycle, displays general spatial and temporal patterns, for example, in the south of Australia the wettest season is in Winter and in the north the wettest season is in Summer. However, the rainfall regime throughout Australia is highly variable and this variability is extreme for the inland Australia. This variability tends to be buffered by the groundwater system but with agriculture has led to large demands for water during droughts.

Figure 2: Average precipitation of Australia (After bureau of meteorology).

Salinization

Salinization refers to degrading of soils and streams by an increase in salinity generated by introduced methods of land use. It does not refer to long standing saline discharge areas located at the terminus of regional groundwater flow paths [6]. It is the result of discharge of local groundwater flow paths [7] initiated by clearing of trees (dryland salinity) or from the introduction of irrigation systems (irrigation salinity).

Dryland salinization of land and water is a growing problem in much of Australia (See figure 3). The first observations of salinization were recorded in western Victoria by George Robinson in

1853 and in south-western Western Australia [9]. The clearing of native vegetation, with roots penetrating well into the unsaturated zone, reduced evapotranspiration; whilst later soil treatment by ploughing and harrowing and replacement by pasture and crops enhanced infiltration. Both changes caused more recharge of the groundwater system. Much of the early work on dryland salinity was undertaken by Soil Conservation Authorities in Western Australia and Victoria [8,9].

Figure 3: Generalized map of dryland salinity in Australia (Modified from QDNR, 1997).

Some 5.7 million hectares of land are now affected by dryland salinization [11]. Rising water tables and saline groundwater inflows are also causing deterioration of the water quality of the nations' rivers and streams [10-12]. For understanding the range of hydrogeologic processes contributing to dryland salinization of land and streams and in choosing effective amelioration measures two national workshops were held in 1998 [13]. Generic hydrogeologic models, shown through 2D vertical slices, were developed as representative of the processes of dryland salinization in a variety of typical landscapes in Australia. Several factors were involved, including topography, salt stores, geology, with the overriding and uniting factor the groundwater flow systems following Tóth's classification of local, intermediate and regional flow paths. The local flow systems have shallow depths, with recharge and discharge areas close together; regional flow systems have deep circulation depths and recharge and discharge areas are separated by considerable distances and they are often overlain by local and intermediate flow systems. A national hydrogeological framework for dryland salinity management was developed [13]. This provided an ordered and strategic approach to the problem of dryland salinity, to further develop national policies for dryland salinity mitigation and management.

A region of focus has been the Murray-Darling Basin, located in SE Australia, where in addition to dryland salinity there is irrigation salinity. In the eastern States, in the Murray-Darling Basin, a major cause of salinization is the spread of irrigation water on arid and semi-arid land, pumped from the Murray R and its tributaries. Ultimately through increased infiltration from irrigation and leakage from the irrigation channels, the water table rose. Consequently, in the depressions where the water table was shallow, salts were concentrated in the soil by evaporation. Similarly, water table mounds under irrigation areas is pushing saline groundwater into the Murray R.

Historically there were interstate disputes about water use and drainage, but by 1915 an agreement was signed by all the relevant States, leading to the establishment of the River Murray Commission in 1917 to share water between the States. With growing concern about of the salinity of the Murray R two major reports were commissioned by the River Murray Commission. They were: Guthridge, Haskins and Davey [14], a comprehensive technical report; and Maunsell and Partners [15], which based on economic analysis, favoured the construction of saline groundwater interceptor schemes between the irrigation districts and the Murray R for its water quality protection. This threat was of particular concern to South Australia, located downstream, where the State capital of Adelaide and the industrial town of Whyalla are dependent on the Murray R for a major proportion of their supplies.

Important features of the Murray Darling Basin management are the interconnection with surface water [16,31] and the disposal of saline water; either from the rising water table or from lines of protector interceptor bores alongside the Murray R [17]. According to Hostetler and Radke [18] there were 150 saline water disposal basins to which this saline water is diverted. Thus, in order to protect agricultural land or river quality.

For the Murray Darling Basin Commission major steps included:1989: Salinity and Drainage strategy produced. Salinity target at Morgan SA is to maintain salinity below 800 uS/cm (480 mg/l TDS). 1995: A cap was imposed on surface water extraction. In 2012: The Basin Plan eventually became law providing a coordinated approach to water use across the Basin’s four States and the Australian Capital Territory. The Plan and its development were contentious with many of the farming communities, particularly in New South Wales, opposed to checks on surface water and groundwater use.

Nitrification and nitrate contamination of groundwater

Overall, the Australian soils appear to have been depleted in N at the time of European settlement, except in northern Australia where there is evidence that there was N in the soil from natural processes [20,21]. But agriculture and a number of other activities brought a boost N in soil and in the hydrologic cycle. The introduction of clover in pastures, with bacteria capable of fixing nitrogen gas from the air (Eqtn1). In turn the ammonium is oxidized to nitrate, by the process of nitrification which also followed with addition of N fertilizers and livestock excreting urine as in Eqtn 2 This step also released H ions. That N which is not used by plants by assimilation (Eqtn 3) can be leached below the root zone and could move downward through the unsaturated zone, often via preferential flow paths, and eventually reach the water table. Although in places which are depleted in oxygen, such as deeper groundwater or wetlands, bacteria can facilitate denitrification (Eqtn 4):

$N_2 + 8H^+ + 6e^- \rightarrow 2.\ NH_4^+$----Eqtn 1

$2NH_4^+ + 6H_2O \rightarrow 2.NO_3^- + 20\ H^+$----Eqtn 2

$NO_3^- + 20H^+ + 16e^- \rightarrow 2.\ NH_4^+ + 6H_2O$---------Eqtn 3

$2NO_3^- + 12H^+ + 10e^- \rightarrow N_2 + 6H_2O$ ----Eqtn 4.

Whilst there is a large store of nitrate in the unsaturated zone in a number places nitrate has reached the water table and the groundwater is contaminated with nitrate [20,22,23] as shown in figure 4. The negative effects are that if the concentration of nitrate exceeds 10 mg/l nitrate it is unsuitable for human consumption [24]. Also The nitrate-rich groundwater can be discharged into streams and lakes causing algal blooms and eutrophication events contributing to fish kills. In addition the release of H ions causes acidification (See Eqtn 2) which can impede plant growth.

Figure 4: Generalized map of nitrate-rich groundwater In Australia (Modified after Bolger and Stevens, [22]).

In terms of treatment of nitrate-rich groundwater there is for the point sources such as landfills and sewerage systems treatment of waste controlled by EPAs. Whilst for agriculture some monitoring is continuing, although relatively little for the unsaturated zone, and more guidance is required on the amount of N fertilizers and the timing of their application.

Nitrification and acidification of soils

Acidification of Australia’s agricultural soils is now widespread and increasing (See figure 5) [25-27], affecting more than half of the intense agriculture land [28]. This acidity has the effect of reducing the productive potential of the soil and in extreme cases is accompanied by aluminium and manganese toxicity.

Figure 5: Generalized map of acid soils in Australia (Modified after de Caritat., *et al*. [30]).

The major cause of soil acidity is the same as that explained in the section above for "Nitrification and nitrate rich groundwater", whereby microbiological facilitated oxidation of fertilizer ammonium ions or fixed nitrogen, accompanied by preferential leaching of nitrate from the soil zone compared to H ions; combined with the export of alkalinity in animal products, trees, crops and hay. Acidity is not seen as a problem for deep groundwater quality in the foreseeable future. since water leaching from soils, would, because of its acidity react with minerals in the unsaturated zone consuming H ions and releasing, for example, calcium and magnesium. The possible exception would be where the regolith is a quartzose sand and where the water table is shallow.

Treatment of soil acidification is by farmers applying crushed limestone (agricultural lime) to increase the pH.

Groundwater sustainability for agriculture

Overall groundwater is regarded as a renewable resource, replenished by recharge from precipitation, the amount of which is the ultimate limit to sustainability of the groundwater resource. Under natural conditions with recharge from precipitation is balanced against groundwater discharge to streams, playas, lakes and the ocean. But with the progressive development of the groundwater resource, beginning in the 1850s this balance has been severely disrupted and groundwater storage reduced. It is estimated for Australia that the average volume of groundwater extracted (for agriculture and other uses) is 5000 billion litre per year. compared with 15000 billion litres per year of surface water consumed [30]. The growth in the amount of groundwater extracted has resulted in overdraft in dozens of places i.e. where there is continued decline in the resource and impact on rivers [31]. Also, near the coast where there been reversal of groundwater movement and there is the threat of seawater intrusion [32]. This depletion of the groundwater resource has happened despite the increase in recharge evidenced salinization caused by the change in land use.

The tapped aquifers belong to groundwater flow systems, driven by recharge, which may be local, intermediate or regional. The extraction has steepened the hydraulic gradient and for some local and intermediate flow systems the regional cone of depression may soon reach the recharge areas, while for others a long time will pass before the recharge is directly impacted. Customarily the hydraulic head of observation bores in the stressed areas are monitored and that together with volume of groundwater extracted is analysed to estimate the sustainable yield of the groundwater resource.

Historically exploratory drilling programs in each State or Territory were carried out, supported by a Federal funding the through the Australian Water Resources Council, to better understand the hydrogeology and discover new groundwater resources. For Australia from the late 1950s the availability of information, combined with improvement in pumps capable of pumping large yields led to the development of thousands of irrigation bores clustered where there were suitable groundwater resources and soils. By the 1970s the official emphasis was shifting from exploration to management within the States e.g. Koo Wee Rup Groundwater Conservation Area (Victoria) declared in 1971; Groundwater (Border Agreement) between South Australia and Victoria, passed in 1986.

Apart from the gaining of information on hydrogeology there was ever present concern by professionals of the risk of overdevelopment. In the case of the Great Artesian Basin, where initially groundwater was artesian i.e. no pumping was required, rapid development followed. However, this behaviour resulted in many previously flowing bores to cease flowing. Concern led to the series interstate artesian water conferences between the affected States, between 1912 and 1928. Later in 1986 The Australian Water Resources Council held a conference on groundwater systems under stress [33] and then a workshop on groundwater allocation [34]. There are dozens of areas, where the groundwater is used for irrigation from large yielding bores and there is the threat of overdraft. Many of the locations of overdraft are where the tapped aquifers are in coastal situations where the aquifers, both unconfined and confined are open to the ocean [35,36].

With the abolishing of the AWRC and later interstate coordination on water came under the COAG umbrella where there was a shift from investigation to management. Underlying all policies and strategies are principles that the groundwater resource is renewable and is to be sustained. In 1992 a system of managerial federalism was introduced by COAG "to achieve an efficient delivery of services in areas of shared responsibility". Key documents were released in 1992, 1994 and 1996 leading in 2004 to the National Water Initiative providing guidelines on the development of Water Management Plans These ambitious management plans seek to avoid overdevelopment and cater for the needs of the environment. There is still an issue about the detail of how to reduce the allocation for these overdraft areas, apart from not issuing any further licences for irrigation bores in those areas. Indeed key issues that still need to be addressed are the definition of sustainable yield depending on the proximity of recharge areas, the predictions of the effect of climate change, the feasibility of artificial recharge and the use of desalinized seawater or treated sewage effluent.

Conclusion

There is scope to integrate research between the different problems. The common factor between the problem areas is the process of groundwater recharge or groundwater inflow.

It is recommended that representative areas be selected for researching and intensive monitoring. The data requirements common to all four problems is rainfall, potential evaporation, hydraulic head of sufficient number of bores to define the hydraulic gradient laterally and vertically. Specifically, the following additional minimum data, needed on each of the problem areas are:

- Salinization - salinity of groundwater, size of salinized area;
- Nitrification and nitrate contamination of groundwater - nitrate concentration in groundwater, nitrate concentration of water in the unsaturated zone, details of fertilizer applications;
- Nitrification and acidification - pH in soil at different levels and locations, details of fertilizer applications
- Groundwater sustainability- locations and pumping schedule of irrigation bores, location of other bores.

For the enduring value of COAG management plans of water resources need to ensure regular reviews, with consequential adjustments to the plans, investigations and ongoing monitoring.

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