Use of water chemistry to identify flow conduits in the porous Gambier Limestone, southeast Australia

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Abstract

The flat-lying Tertiary Gambier Limestone in southeastern Australia is a porous, high-yielding, largely unconfined aquifer; groundwater movement is by both intergranular and conduit flow. Springs within a few kilometers of the coast show elevated chloride levels, due to seawater input rising up vertical conduits from depths of 100-200m; these conduits are probably being actively dissolved by mixing corrosion. The chloride and isotopic composition of cenote lakes is variable, reflecting shallow local input of dilute water directly through open joints into the regional, more saline groundwater flow. Most cenote lakes show the effects of conduit input, but some are apparently fed only by porous flow. Conduit flow within the inland part of the aquifer is more widespread than previously realised.

1. Introduction

The Mt Gambier region in southeastern Australia (Fig. 1) is underlain by a porous, high yielding, largely unconfined limestone aquifer, the Gambier Limestone. Because of the lack of surface water resources, the high quality (TDS generally 300-600 mg/L) groundwater is extensively used for irrigation, town water and stock and domestic use (total ~12,000 ML/year). The reliance on groundwater from a limestone aquifer is unusual in Australia, where aquifers of this lithology contain only ~20% of total groundwater and account for about 3% of total water use (SMITH 1988).

The Gambier Limestone contains both primary intergranular and secondary karstic porosity. Along the coast, major springs issuing from cave systems probably represent 75-80% of total discharge from the aquifer, intergranular porous flow contributing only 20-25% (WATERHOUSE 1977). However, behind the coast it was believed that groundwater movement is predominantly as intergranular flow, because the karst conduits do not form an interconnected network (HOLMES & WATERHOUSE 1983). In this paper the water chemistry of the groundwater will be used to show that conduits are an integral part of groundwater flow throughout the aquifer.

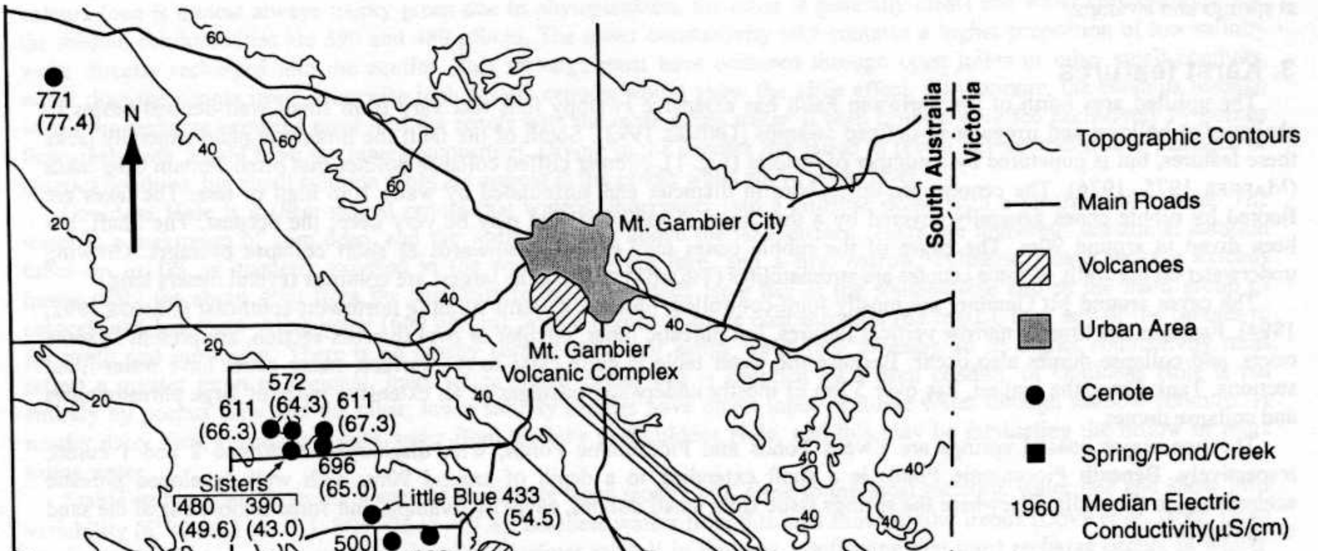

Figure 1: Location of the studied area

2. Geological, geographical and hydrological setting

The Gambier Limestone accumulated on an open, cool temperate, shallow marine shelf from the latest Eocene to earliest Middle Miocene (Smith *et al.* 1995). It is composed predominantly of sand-sized fossil fragments cemented by thin rims of calcite. Primary porosity, both intra- and inter-particle, ranges from 30-50% (Love *et al.* 1993). There is also a secondary karstic porosity, evident as cave systems generally developed along the dominant northwest-southeast jointing in the limestone (described further below). In parts of the aquifer dominated by intergranular groundwater flow, hydraulic conductivity varies from 2-30 m/day, with velocities of 5-50 m/year. Regions with karst fissure development have much higher hydraulic conductivities of 130-270 m/day, and velocities in the conduits feeding large springs can be of the order of cm/sec (Waterhouse 1977; Emmett & Telfer 1994; Love *et al.* 1993).

The Gambier Limestone is essentially flat-lying, but has been offset along the northwest-trending Tartwaup Fault. The upthrown northeastern side of the fault forms a plateau at a higher elevation (60-70m) than the limestone plain to the south (30-40m), which slopes gently to the sea. The limestone is as little as 10m thick on the upthrown side of the fault, but thickens southwards to 300m at the coast. The limestone is covered by thin soils; south of Mt Gambier are extensive areas of limestone pavement where the soils have been stripped. There is little case-hardening and no calcrete development on the weathered limestone surface.

The climate is characterised by moist cool winters and hot dry summers. Rainfall in the area is 700-800mm, and decreases to the north. Mean daily maximum and minimum temperatures range from 22-24°C and 12-14°C in January to 13-14°C and 5-7°C in July (respectively). Potential evaporation exceeds rainfall from October to April; the excess precipitation is ~150mm for the whole year, and ~300mm for the winter months alone (Waterhouse 1977; Love *et al.* 1993). Calculations based on discharge from the coastal springs and water chemistry indicate an average recharge of 100-250mm (Waterhouse 1977; Allison & Hughes 1978), so infiltration is 15-35% of rainfall. Recharge is through the thin soils and bare rock pavements of porous limestone, as well as open joints and dolines (described below). Recharge has increased following clearing of the native vegetation (Allison & Forth 1982), and is exceptionally high by Australian standards. In the Southeast Australian Drainage Division, of which the Mt Gambier area is a small part, the average infiltration is less than 2% of rainfall (Smith 1998).

Apart from the allogenic Glenelg River on the eastern margin, the Mt Gambier area has no surface drainage network and the only perennial streams issue from coastal springs. The watertable is well-defined and slopes gently towards the coast (1:1000-2000), except along the Tartwaup Fault, where the hydraulic gradient is substantially steeper (1:150-200). On the limestone plain south of the fault, depth to the water table decreases coastwards from 10-20m to intersect the ground surface at springs and swamps.

3. Karst features

The uplifted area north of the Tartwaup Fault has extensive swampy flats that vary from small well-defined basins to shallow flat hollows and irregular ill-defined swamps (Grimes 1992). South of the fault the limestone plain generally lacks these features, but is punctured by a number of cenotes (Fig. 1), circular cliffed collapse dolines that often contain deep lakes (Marker 1975, 1976). The cenotes are up to 60m in diameter and surrounded by walls 10m high or less. The lakes are floored by rubble cones generally covered by a thin layer of sediment, and may be very deep; the deepest, The Shaft, has been dived to around 90m. The edges of the rubble cones may extend downwards as short collapse passages. Growing underwater on the walls of some cenotes are stromatolites (Thurgate 1995); the largest are columns several meters long.

The caves around Mt Gambier are mostly joint-controlled, phreatic systems running northwest-southeast (Grimes 1992, 1994). Passages are usually narrow vertical fissures, but phreatic tubes, circular or oval in cross-section, are present in some caves, and collapse domes also occur. Because the water table is quite close to the surface, many caves have water-filled sections. Tank Cave, the longest, has over 5 km of mostly underwater passages as an extensive maze of large phreatic tubes and collapse domes.

The two major coastal springs are Ewens Ponds and Piccaninnie Ponds, with discharges of around 2 and 1 cumec respectively. Beneath Piccaninnie Ponds is a shaft extending to a depth of around 90m, with well developed phreatic sculpturing on the walls. Elsewhere the springs issue from small dolines, caves or swamps, and some bubble out of the sand on the beach.

4. Water sampling and analysis

Water samples were collected every month from fourteen cenotes and five springs over the period July 1998 to July 1999. Field measurements of temperature, conductivity and pH were taken when each sample was collected, and the samples were analysed in the laboratory for major anions and cations. Charge balances were generally <4%. The results show well-marked seasonal variation at many sites, but this paper will discuss only the overall water chemistry, using median values of conductivity and chloride concentration, along with stable isotope data.

5. Spring waters

The most saline waters, with the highest chloride concentrations, occur in springs and dolines within several kilometers of the coast; median values progressively increase towards the coastline, from 50-80 mg/L inland to 500-600 mg/L at Piccaninnie Ponds, less than 1 km from the coast. The salinity is derived from the seawater wedge that intrudes inland within the porous limestone aquifer. The salinity profile from a borehole adjacent to Piccaninnie Ponds shows the fresh/saline interface is at about 150m depth, and this is verified by geophysical data for the area (Waterhouse 1977). The watertable at the site is 3-4m above sea level, so from the Ghyben-Herzberg relationship the interface should be at 120-160m. The shaft at Piccaninnie Ponds extends down at least 90m; the fact that it brings quite saline water to the surface indicates that it extends substantially deeper. Thus vertical conduits at least 150m deep must be present beneath all the springs and dolines with high salinity water. The most inland sites with elevated levels of chloride are about 3 kilometers from the coast and the water table is 4-6 m above sea level, indicating that the saline water is coming up conduits 160-240m deep. The deep flow paths implied by these figures are verified by the fluid potential distribution in the Gambier Limestone based on the potentiometric head measured in boreholes (LOVE *et al.* 1993).

It has long been recognised that the bulk of groundwater discharge from the Gambier Limestone along the coast is from conduit-fed springs rather than porous intergranular flow (WATERHOUSE 1977). However, the water chemistry data show that these conduits are more common and deeper than previously suspected. Mixing corrosion is likely to be actively enlarging these conduits at present, and could well be largely responsible for their origin.

6. Cenote waters

The lakes in the cenotes represent easily accessible windows into the water table, and because of their generally substantial depth, they provide information about both deep and shallow flow within the aquifer. Excluding the coastal region discussed above, water in the cenotes shows a general coastwards decrease in salinity, from ~800 µS/cm to 500-650 µS/cm, accompanied by decreases in major ions, particularly chloride, from ~80 mg/L to 40-60 mg/L; borehole waters show a similar trend (LOVE *et al.* 1993). This is due to the fact that the uplifted plateau north of Tartwaup Fault forms a groundwater divide. Evaporation in the swamps of this area (Dismal Swamp), which has lower rainfall than the plain to the south, provides a relatively high salinity input into the groundwater. This higher salinity water flows southwards to the coast, and along the way it is diluted by low salinity water which infiltrates rapidly through the limestone. Away from the coast there are no swamps on the limestone plain south of the fault, so there is no input of higher salinity water due to open water evaporation; the surface area of the cenote lakes is too small for evaporation to affect the chemistry significantly.

Within this regional pattern there is considerable variation, evident also in the borehole data, and LOVE *et al.* (1993) proposed that this was due to local recharge. This local input could occur directly through open joints and dolines, or through porous intergranular recharge (e.g. on exposed limestone pavements). The local inputs should vary in chemistry according to the speed of infiltration; direct input would be expected to have very low salinity, whereas recharge through porous flow would be more saline due to the effects of evapotranspiration above the water table. The water chemistry data from the cenotes provide clear evidence that while both processes occur, direct input is significant in many places.

The Sisters cenotes are a pair of collapse dolines separated by a soil-covered rubble pile only 20-40m wide, the walls rise 9m above the lakes which are up to 20m deep. Despite the closeness of the two lakes, they have substantially different colours (one is almost always murky green due to phytoplankton, the other is generally clear) and water compositions, e.g. the median conductivities are 390 and 480 µS/cm. The lower conductivity lake contains a higher proportion of low salinity water directly recharged into the aquifer. This recharge must have occurred through open joints or other small conduits, rather than the cenote itself, otherwise both Sisters cenotes would show the same effect. Furthermore, the conduits through which the recharge occurred must feed the cenote with the more dilute water. If both cenotes were fed exclusively by porous flow, then both would have the same composition. Diving in the cenotes has failed to reveal any enterable cave passages or obvious conduits, but small solution tubes are present in the cenote walls above water level.

Gouldens Hole is a sheer-walled cenote that widens underwater into a collapse dome with a central rubble cone. The water is a maximum of 26m deep, and the walls rise 12m above the lake surface. There are numerous horizontal solution tubes up to 1m in diameter exposed in the walls above the lake, and a dry, narrow, cylindrical cave passage extends horizontally for about 40m from the southeastern side. Gouldens Hole lies at the southeastern end of the main group of cenotes, and has more saline water (660 µS/cm), with a higher chloride concentration (63 mg/L), than any of the cenotes to the north and northwest. There is no nearby surface source of saline water (e.g. swamp), so its higher conductivity must reflect a greater input of regional, more saline water. Either this is supplied by a deep conduit, or Gouldens Hole is fed entirely by porous flow and the other, lower salinity cenotes have direct input of dilute water through shallow conduits. A nearby dairy farm regularly pumps water from the lake in Gouldens Hole, and this may be facilitating the inflow of more saline water.

Stable isotope data from the waters of the cenote lakes mostly plot close to the local meteoric water line and show little variability ($\delta^{18}O$ –4.3 to –5.5; $\delta^{2}H$ –26 to –31.8); borehole waters from this area show similar trends (LOVE *et al.* 1992; LOVE *et al.* 1993). The average composition is that of winter rainfall in the area, confirming that most recharge occurs in winter. The fact that most samples plot close to the meteoric water line indicates that infiltration is rapid, without isotopic fractionation due to evaporation. The sample from Little Blue Lake does not follow this trend (-3.0, -19); its separation from the meteoric water line could indicate the effects of evaporation, but this is not reflected in its chloride composition (55 mg/L), which is lower than that of nearby cenotes (56-65 mg/L), and ALLISON (1974) showed that evaporation from this lake is relatively small. Instead the outlier probably represents an individual rainfall event with a different, isotopically heavier composition, more typical of summer rainfall. Little Blue Lake has a slow groundwater throughflow, estimated using tritium balance to be 2-4 years (ALLISON 1974), and is probably not connected to conduits in the limestone, being fed largely if not entirely by porous intergranular flow. The isotopically heavy rainfall event recorded by the Little Blue Lake sample almost certainly recharged the limestone aquifer over a much bigger area than just around Little Blue Lake; in other cenotes this water has been replaced by relatively rapid conduit-fed input of subsequent winter rainfall. The water in Little Blue Lake is colder in winter (12.4°C) and warmer in summer (24.3°C) than most other cenote lakes (median 13.9, 20.6°C respectively); this is not due to the lake size or aspect. Temperatures in most cenote lakes are evened out by continuing, relatively rapid input of regional groundwater at 15-16°C (the uniform temperature at several meters depth in this area). Little Blue Lake, lacking conduit input, is relatively isolated and shows a greater response to summer-winter fluctuations in surface temperature.

7. Relative importance of intergranular and conduit flow

Although there is no doubt that along the coast most groundwater flow occurs through conduits, the inland portion of the Gambier Limestone has been regarded as predominantly a porous flow aquifer. It clearly has many of the characteristics of a porous aquifer, not the least of which is a substantial intergranular porosity, along with a well-defined water table and appropriate values of hydraulic conductivity. However, even inland much of the groundwater movement is probably through conduits. The water table has a very low gradient, and this, together with values of hydraulic conductivity of up to 270 m/day in places, indicates high permeability and conduit flow. In addition, substantial cave systems are known within the limestone.

The water chemistry data from the cenote lakes show that there is considerable local recharge of the aquifer through small, shallow conduits, and these conduits probably feed most of the cenotes. There are likely to be deeper conduits present as well. Jointing in the limestone is dominantly northwest-southeast; this determines cave development in the area, and the smaller conduits probably also have this orientation. A northwest-trending potentiometric low in the water table, the Ewens Ponds-Mount Schank Trough (WATERHOUSE 1977), extends across the plain south of Mt Gambier, and includes the highest concentration of karst features (cenotes and springs) in the area. This trough probably reflects a greater concentration of joint-controlled conduit flow, and verifies the importance of conduit flow through much of the Gambier Limestone.

This finding has implications for management of the groundwater resources of the aquifer. In the past, dolines often served as convenient disposal sites for contaminated waste, including sewerage and cheese factory effluent, resulting in pollution of the aquifer. The rapid appearance of contaminated groundwater in unexpected locations indicated the presence of karst conduits (EMMETT & TELFER 1994). Waste water disposal is now more tightly controlled, and direct pollution of this type is no longer such a problem. However, on the limestone plain south of Mt Gambier the aquifer is heavily exploited for pasture irrigation, and a substantial drop in the water table has caused consternation. In areas of the aquifer with high permeability due to conduit flow, drawdown cones around pumping bores are shallow but areally extensive, and could potentially have a regional rather than local effect. This needs to be clearly recognised when determining the management plan for the groundwater resource.

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