

Teaching Invisible Groundwater Systems: Modelling Aquifers for Geographical and Environmental Understanding

Ali Rad Yousefnia

School of Architecture, Design and Planning, University of Queensland, St. Lucia, Brisbane, QLD 4072, Australia

Stephen Hughes

School of Mathematics and Physics, University of Queensland, St. Lucia, Brisbane, QLD 4072 Australia

UQ College, University of Queensland, St. Lucia, QLD 4072, Australia

Peter Schouten

UQ College, University of Queensland, St. Lucia, QLD 4072, Australia

Catherine Clemot

School of Education, University of Queensland, St. Lucia, QLD 4072, Australia

Abstract

Groundwater systems are central to geographical and environmental education, yet their hidden and process-based nature can make aquifers difficult for students to conceptualise. At a time when groundwater depletion, land subsidence, climate stress, and rising water demand are intensifying across many parts of the world, aquifers need to be understood not only as hydrological systems but also as pedagogical tools for teaching environmental change, resource use, and human–environment relations. This paper argues that aquifers offer a productive bridge between Humanities and Social Sciences (HASS) and Science, Technology, Engineering, and Mathematics (STEM) disciplines by connecting physical processes to questions of Geography, governance, infrastructure, sustainability, and environmental justice. The paper first reviews global cases of aquifer depletion and associated land subsidence, including India, California, Iran, China, Indonesia and Mexico, while outlining the physical principles that help explain aquifer compaction. It then turns to the Great Artesian Basin (GAB) in Australia as a real-world teaching case through which scale, pressure, springs, geothermal properties, and resource use can be made more legible. Building on this, the paper introduces a simple physical aquifer model for secondary education, with potential for use in foundation-level tertiary subjects, and demonstrates its value for strengthening geographical and environmental understanding.

Keywords: Groundwater education; Aquifer modelling; Environmental literacy; Geographical thinking; HASS–STEM learning; Great Artesian Basin

Introduction

Groundwater systems have long played a central role in shaping human settlements and societies, while also providing an important entry point for geographical and environmental education. Their hidden and process-based nature makes aquifers especially valuable for teaching students how physical systems, landscapes, resources, and human decisions are connected. This importance was evident in early human communities during the Neolithic era, when water storage and management techniques remained relatively primitive. As people gradually shifted from hunting and gathering to more permanent settlements with agriculture-based lifestyles, reliable access to fresh water became increasingly critical. Because rivers and lakes were not always dependable throughout the year, one of the most significant discoveries was the recognition of an underground, largely invisible, source of fresh water: aquifers.

As Wittfogel (1957) argues in *Oriental Despotism*, the control and bureaucratisation of water in civilisations such as Egypt and the Rio Grande Pueblos contributed to their strength within hydraulic economies, supported by artificial wells, cisterns, and large man-made reservoirs. From the past to the present, however, reliance

has shifted increasingly towards underground freshwater sources; for example, aquifers supply around 80% of drinking water in the United States (Arthurs, 2019).

In many parts of the world, rapid urbanisation is placing growing pressure on water systems, including the surface and underground sources on which cities depend. As highlighted in *World urbanization prospects: The 2018 revision*, the world passed a major demographic threshold in 2018, when 55% of the global population lived in urban areas, with this figure projected to reach 68% by 2050 (United Nations Department of Economic and Social Affairs, 2019). This unprecedented concentration of population is taking place in urban areas that occupy only around two to three per cent of the Earth's land surface (Liu et al., 2014). At the same time, urban water demand is expected to increase by 80% by 2050, a trend likely to be intensified by the effects of climate change (Flörke et al., 2018). Together, these pressures make groundwater systems increasingly important to understand, particularly where aquifers are drawn upon to support urban growth, agriculture, industry and everyday water use.

In parallel, both the quality and quantity of usable water available from aquifers are highly sensitive to climate change (Ferguson & Gleeson, 2012). Recent research also shows that climate change can exacerbate existing social inequalities by widening the gap between affluent and disadvantaged groups, particularly where mitigation and adaptation strategies depend heavily on individual wealth and resources (Zahnow et al., 2025). The cases discussed in the following section illustrate these relationships more directly. In north India, for example, summer monsoon drying and winter warming are accelerating groundwater depletion, while groundwater pressures are unevenly experienced across regions and communities (Mishra et al., 2024; Sobti & Rad Yousefnia, 2024). These conditions raise important questions about sustainable water use and equitable access to clean water and sanitation, identified by the United Nations as Sustainable Development Goal (SDG) 6, as one of the 17 global goals. SDG 6 remains a key priority in the pursuit of a safe and just future, particularly related to water. Recent United Nations reporting shows that by 2024, 74% of the global population had access to safely managed drinking water, although water stress remains severe in several regions (United Nations Department of Economic and Social Affairs, 2026).

Aquifer Depletion, Climate Stress, and Land Subsidence

Although access to water is vital for any society and community, existing research shows that the overexploitation of groundwater, coupled with the effects of climate change, is dramatically affecting the condition of aquifers across key mid-latitude regions (Wu et al., 2020). This makes education on climate change, groundwater systems and water use vital, especially in the Global South, where communities are often more exposed to climate impacts while also having limited access to adequate teaching and learning materials on these topics (Bardullas et al., 2025).

India provides a particularly significant example of these pressures. As the largest groundwater user globally, India abstracts an estimated 251 cubic kilometres of groundwater per year, with 89% of this abstraction used for irrigation (Pointet, 2022). A recent India-focused assessment similarly emphasises the centrality of groundwater to national water security, reporting that groundwater meets about 63% of irrigation demand, 85% of rural water needs, and more than 50% of urban water requirements, with nearly 90% of annual groundwater withdrawals used for irrigation (International Water Management Institute, 2026). This reliance has contributed to a groundwater sustainability crisis: around 27% of districts are affected by over-extraction and/or water quality problems, while 11% of national assessment units are classified as over-exploited and 14% as semi-critical or critical (International Water Management Institute, 2026). These pressures are unevenly experienced across regions and communities, making groundwater depletion not only a hydrological issue but also a question of water inequality, reliable access, and everyday water security (Sobti & Rad Yousefnia, 2024). Together, these pressures have contributed to the growing description of aquifer decline and water-supply stress as an underground drought.

A major contributor to this crisis is the expansion of groundwater extraction for agriculture under weak regulatory control, alongside electricity subsidies that have reduced the marginal cost of pumping and encouraged more intensive use of bore pumps (Gupta, 2023; Rizvi et al., 2025). In Punjab, for instance, the shift from flat-rate to free farm electricity pricing in February 1997 was associated with groundwater depth increasing by 1.9 metres more than in neighbouring Haryana, an effect equal to around 22% of Punjab's baseline groundwater depth, demonstrating a measurable link between energy policy and aquifer decline (Gupta, 2023). These studies found that free electricity contributed to a sharper rise in the number of electric-operated tubewells and in average pump horsepower, indicating that

the policy not only increased access to pumping but also expanded the technical capacity for more aggressive extraction.

Aquifer depletion in India is being further accelerated by climatic stress. Satellite and hydrological model estimates show that north India lost around 450 km³ of groundwater between 2002 and 2021, with depletion occurring at a rate of roughly 1.5 cm per year under conditions of summer monsoon drying and winter warming (Mishra et al., 2024). These findings suggest that reduced monsoon rainfall does not act in isolation but weakens groundwater recharge while simultaneously increasing irrigation demand, thereby intensifying the pressure created by millions of privately operated borewells and the broader overdependence of Indian agriculture on aquifers (Mishra et al., 2024). More broadly, recent review work confirms that agricultural overuse remains one of the central drivers of groundwater depletion in India, reinforcing the argument that the present crisis is not only climatic but also deeply shaped by subsidy structures, extraction practices, and the absence of effective limits on pumping (Rizvi et al., 2025). Meanwhile, on the positive side, projects such as Bilkha Bawari, a community-based water harvesting and management project, point to more community-based and locally-grounded approaches to water harvesting, storage, and management that reduce excessive reliance on aquifers (Sobti & Rad Yousefnia, 2024).

Groundwater depletion and water overconsumption are not confined to India; however, it represents a broader global crisis with major environmental and urban consequences. In California's Central Valley, groundwater declined by around 3 km³ per year between 1950 and 2009, with projections suggesting that continued overuse, combined with the effects of climate change, could increase annual losses by roughly 31–39% and up to 40–70% annually in some areas (Alam et al., 2019). In Iran, the consequences are particularly severe, with aquifer depletion closely linked to extensive land subsidence across large parts of the country. Some estimates suggest that around 56,000 km² of Iran's territory is affected by land subsidence (Golian et al., 2021; Motagh et al., 2008; Tabari & Eilbeigi, 2025); in particular, the Tehran-Shahriar Plain has experienced a major ground-level decline due to unregulated groundwater extraction and long-term aquifer stress (Azarakhsh et al., 2022; Haghighi & Motagh, 2019).

Similar patterns can also be seen in other parts of the world, highlighting the global consequences of these matters. In the North China Plain, groundwater overexploitation has caused prolonged aquifer depletion and extensive land

subsidence, with groundwater storage declining by 17.8 ± 0.1 mm per year between 1971 and 2015 and groundwater levels in some areas falling by more than one metre annually (Gong et al., 2018). Given that groundwater supplies around 60% of drinking water and 70% of irrigation water in the region, these changes have been associated with increased flood risk, infrastructure damage, seawater intrusion, and broader ecological and socio-economic stress (Du et al., 2024). Jakarta in Indonesia provides another significant example, where intensive groundwater extraction has contributed to severe land subsidence and increased flood risk; these pressures have also been identified as one factor contributing to Indonesia's decision to relocate its capital to East Kalimantan (Takagi et al., 2021). Comparable pressures are also visible in Mexico City, where heavy reliance on groundwater has contributed to land subsidence rates of up to 50 cm per year (Chaussard et al., 2021), and in California's San Joaquin Valley, where land subsidence reached about nine metres due to aquifer-system compaction caused by over-pumping (Alam et al., 2019).

A major problem with unsustainable extraction from aquifers, therefore, is not only the depletion of vital water resources for domestic, commercial, industrial, and agricultural use, but also the damage it causes to the built environment through land subsidence. When groundwater is removed faster than aquifers can recharge, the ground above can compact and sink, creating uneven settlement across urban areas. This process is especially destructive because it does not simply reduce water availability; it also places pressure on buildings, roads, bridges, pipelines, sewer networks, and other forms of infrastructure that depend on ground stability. In this sense, aquifer depletion is beyond a hydrological hazard. It turns out to be an architectural and urban hazard, as differential subsidence can undermine structural integrity, increase maintenance costs, and deepen risks for already vulnerable communities (Chaussard et al., 2021).

This process can also be explained physically. As groundwater is removed, pore water pressure declines and, following Terzaghi's effective stress principle (Terzaghi, 1925), the effective stress acting on the soil skeleton increases, causing aquifer materials to compact (Helm, 1975). Aquifer depletion is therefore not merely about water loss, but also about the mechanical compression of subsurface layers that can eventually produce land subsidence (Galloway et al., 1999; Gambolati & Freeze, 1973; Hoffmann et al., 2001) and cause greater damage under and above the ground (Chaussard et al., 2021).

This becomes even more significant in very large aquifer systems. Rather than passive underground reserves, such formations are dynamic geological structures whose scale, pressure, and storage capacity confer significant environmental, mechanical, and spatial significance. As aquifers increase in size, so too does the volume of water they contain, the territorial reach of their influence, and the consequences of their depletion. This is particularly evident in the world's largest aquifer systems, where groundwater must be understood not simply as a hidden local resource, but as a regional force shaping landscapes, ecologies, and human settlement. Among many international examples, the Great Artesian Basin stands out as one of the largest and most significant, making it a particularly important case (Figure 1).

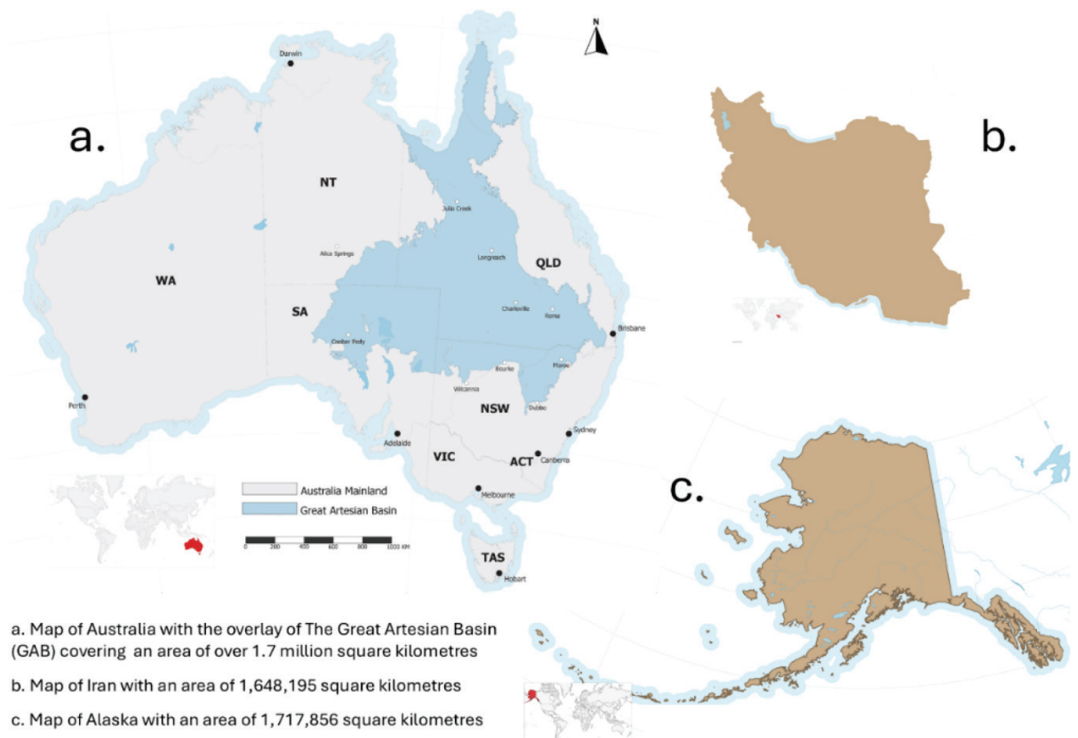
To advance multiple Sustainable Development Goals and to help avoid the destructive consequences of aquifer depletion and land subsidence in the context of the global climate emergency, aquifers need to be understood both as hydrological systems and as pedagogical tools in educational settings (Arthurs, 2019). Using students' existing conceptions of groundwater as resources for teaching can help educators identify and challenge common misconceptions about how groundwater is stored and moves through aquifer systems (Arthurs, 2019). As discussed

above, the use of local and recognisable aquifer examples can make groundwater more legible to students by linking abstract hydrological processes to real landscapes, social histories, and everyday patterns of water dependence. This is especially valuable in geography education because aquifers can connect physical processes with questions of settlement, infrastructure, sustainability, resource use, and environmental responsibility across both Humanities and Social Sciences (HASS) and Science, Technology, Engineering, and Mathematics (STEM) disciplines.

The Great Artesian Basin: A Groundwater System in Australia and a Real-World Teaching Case

In the Australian case, the Great Artesian Basin (GAB) provides, perhaps, the most compelling example for this purpose. Extending beneath parts of Queensland, New South Wales, South Australia, and the Northern Territory, the Basin covers almost 1.7 million square kilometres, or just over one-fifth of the Australian continent, making it Australia's largest groundwater basin and one of the largest underground freshwater resources in the world (Department of Climate Change, Energy, the Environment and Water, 2025).

Figure 1: Comparative maps showing the approximate areal extent of the GAB alongside Iran and Alaska to situate its large territorial scale in relation to other recognisable land masses on the world map. Maps produced by Ali Rad Yousefnia in R and finalised in Adobe Photoshop. Generative AI was used only to assist with the refinement of R code, which was subsequently checked and executed by the author.



Data sources: Australian Bureau of Statistics (2021), Bioregional Assessment Program (2016), Natural Earth (n.d.).

Figure 1 presents the GAB in spatial perspective through three related maps. Figure 1(a) shows the Basin beneath mainland Australia, highlighting its continental scale and its extension across multiple states and territories. Figures 1(b) and 1(c) place the GAB alongside Iran and Alaska to provide a comparative sense of its area. Together, the maps emphasise that the GAB is not a localised groundwater formation, but a hydrogeological system of exceptional spatial scale.

The volume of water stored within the GAB is estimated at approximately 64,900 million megalitres, or 64,900 km³ (Jones et al., 2020), underscoring the exceptional scale of this groundwater system. This volume is approximately 130,000 times greater than that of Sydney Harbour (Sharma & Apoorva, 2025). The GAB also contains approximately 2.75 times the volume of Lake Baikal in Russia, the world's largest freshwater lake, and exceeds the combined volume of the North American Great Lakes (Assani et al., 2016; Touchart, 2012). In the context of Australia, as the driest inhabited continent, the existence of such a substantial subsurface water reserve is especially noteworthy (Taylor et al., 2022).

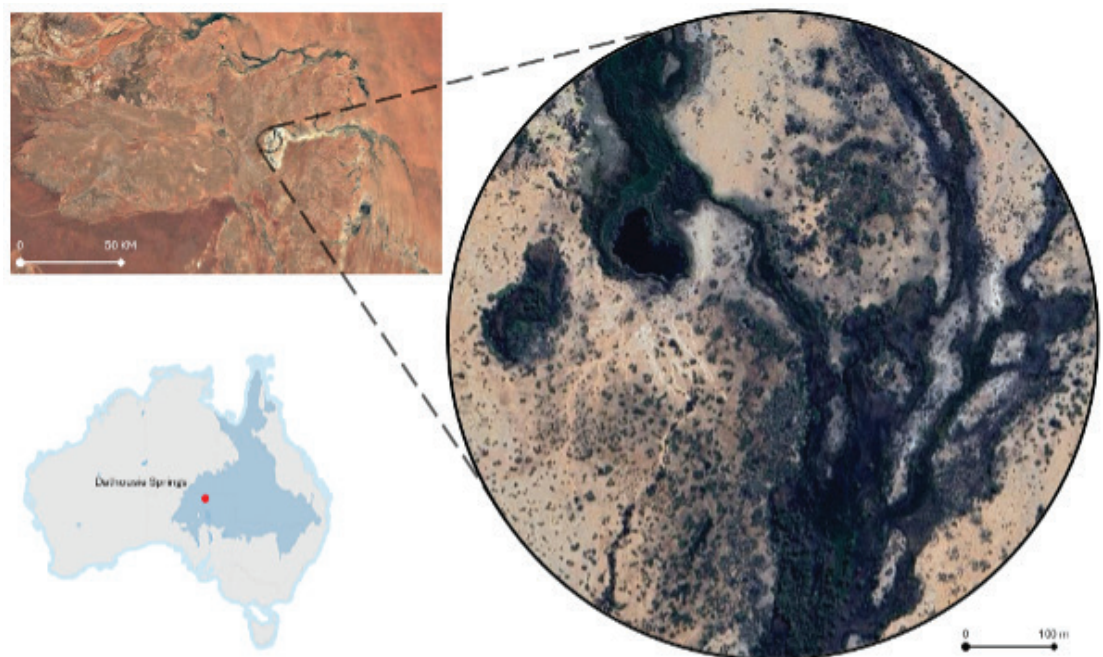
Aquifers can sustain perennial springs, providing flows that persist throughout the year rather than fluctuating strictly with seasonal surface conditions (Davis et al., 2017). This is particularly significant in Australia, where many rivers and

surface water systems are highly variable and may cease to flow for extended periods under dry climatic conditions (Costigan et al., 2017). In this respect, groundwater systems such as the GAB play an important role in maintaining more reliable water discharge across arid and semi-arid regions.

Within the GAB, mound springs also hold longstanding cultural significance for Aboriginal peoples, having provided reliable water in arid environments for thousands of years while forming important sites within cultural stories, travel routes and spiritual relationships with Country (Moggridge, 2020; Rossini et al., 2020). Dalhousie Springs in northern South Australia (Figure 2) provide a particularly significant example. Known as Irrwanyere, or “the healing springs”, the springs have been associated with healing, spiritual purposes and food resources, while their cultural significance and subsequent environmental degradation following European settlement demonstrate the close relationship between groundwater, cultural heritage and care for Country (Erfurt, 2021; Moggridge, 2020). More broadly, these connections reinforce the importance of recognising Aboriginal knowledge and custodianship in the ongoing management and conservation of GAB springs (Rossini et al., 2020).

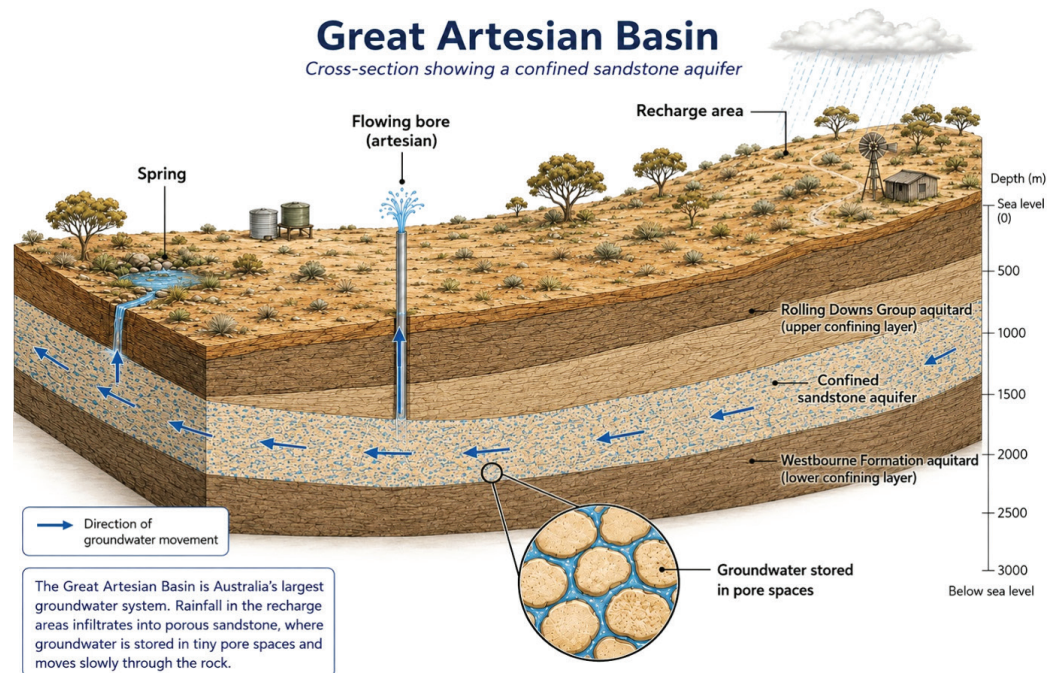
As shown in Figure 3, the cross-section of the GAB illustrates groundwater movement through

Figure 2: Satellite view of Dalhousie Springs in northern South Australia, showing the groundwater-fed spring environment within the wider arid landscape of the GAB. The maps locate Dalhousie Springs within the GAB and provide regional and local spatial perspectives.



Compiled by Ali Rad Yousefnia using Google Earth satellite imagery and GAB spatial data.

Figure 3: Simplified schematic cross-section of the GAB, illustrating recharge, groundwater movement through a confined sandstone aquifer, artesian discharge through a spring and flowing bore, aquitards, depth, and groundwater storage within pore spaces. Image by Ali Rad Yousefnia, produced using AI image generation and subsequently revised by the author. The conceptual representation is based on Radke et al. (2000) and Reinfried (2006), with aquitard characteristics and hydro-stratigraphic interpretation informed by Harrington et al. (2013) and GAB hydrogeological information from Geoscience Australia.



deep, confined sandstone aquifers rather than through open underground channels or rivers. This distinction is important pedagogically because students may misinterpret groundwater as being stored in subsurface lakes, caves, rivers or “water veins”, rather than within the pore spaces and fractures of permeable rock. Reinfried (2006) shows that such misconceptions can persist and that visual representations may either challenge or reinforce students’ mental models of groundwater. In this image, the aquifer is represented as a porous, water-saturated sandstone layer confined by less-permeable aquitards, with arrows indicating the slow movement of groundwater through the rock.

A notable feature of the GAB is that groundwater can emerge at the surface under artesian pressure, including in locations that appear topographically flat. This occurs because water recharged in elevated areas moves through confined aquifers and remains under pressure until released through springs or bores (Habermehl, 2020). Dalhousie Springs in northern South Australia provide a natural example of this process, where thermal groundwater from the GAB reaches the surface as a substantial spring complex (Erfurt, 2021), as shown in Figure 2. Another example is Birdsville in Queensland in Figure 4, located approximately 1,300 kilometres inland from the eastern coastal ranges. As shown



Figure 4: Hot water emerging from an artesian bore in Birdsville, Queensland. Image by Stephen Hughes.

in Figure 3, groundwater travels through deep confined layers, with some sections reaching depths of around 3 kilometres below the surface. At such depths, groundwater temperatures may become very high because subsurface temperature generally increases with depth through the geothermal gradient (Erfurt, 2021) and water discharged at the surface can present practical and safety concerns (Radke et al., 2000).

Beyond the recharge, confinement, and artesian discharge illustrated in Figure 3, Figure 4 also highlights the thermal properties of groundwater in parts of the GAB. In some locations, water emerging from artesian bores is hot enough to create opportunities for geothermal use.

Birdsville provides a notable example, where artesian water was used to support electricity generation through a geothermal plant. By 2004, the Birdsville geothermal power plant had a net output of 80 kWe and a capacity factor exceeding 95 per cent, supplying just under one-third of the town's electricity demand and demonstrating that the significance of the GAB extends beyond water provision to broader questions of energy provision and regional infrastructure (Huddleston-Holmes, 2014).

As a teaching case, the GAB makes visible the multiple dimensions of aquifers, from groundwater flow and artesian pressure to springs, heat, and resource use. The next section builds on this complexity by introducing a simpler aquifer model that can support explanation and learning in the classroom.

A Physical Aquifer Model: A Classroom Experiment

Models can provide useful teaching tools for representing complex scientific phenomena by connecting theoretical ideas with processes that may be difficult to observe directly (Harrison & Treagust, 1998; Oh & Oh, 2011). To translate the scale and complexity of real aquifer systems into a form that can be directly observed in teaching environments, a simple physical model can be constructed for classroom use. Although the hydrogeology of aquifers involves complex subsurface processes, including variations in geological materials, confinement, recharge pathways, and groundwater flow, a simplified experiment can make key principles

of groundwater storage, pressure, and flow more visible and accessible for school and undergraduate students. In this sense, the model functions not as a complete representation of natural groundwater systems, but as a deliberately reduced physical analogue through which foundational processes can be introduced and discussed. Making these limitations explicit also provides an opportunity for educators to discuss with students what the model represents, what it simplifies, and how a physical model differs from the natural system.

The pedagogical value of the model is further strengthened by its relevance to existing curriculum frameworks. Across different levels of the Australian Curriculum and related Queensland senior secondary syllabuses (Australian Curriculum, Assessment and Reporting Authority, 2022; Queensland Curriculum and Assessment Authority, 2024), the model can be used to connect groundwater processes with broader topics such as material properties, Earth systems, renewable resources, and water management. The strongest links are with Year 7 Geography through examining water as an environmental resource, Year 10 Science through Earth system interactions, Year 10 Geography through environmental change and management, and senior Earth and Environmental Science through the sustainable use and management of groundwater. In this respect, the model is valuable not only as a classroom demonstration but also as a way of linking physical processes, environmental understanding, and applied discussion across both STEM and HASS-oriented teaching contexts. This may be particularly

Figure 5: Schematic diagram of a simple physical aquifer model. The model uses a transparent, flexible tube filled with gravel, with one side representing the aquifer recharge region and the other representing a spring. Differences in water level generate pressure that drives water flow through the gravel-filled tube, while the central riser and tap demonstrate artesian discharge. Diagram by Stephen Hughes.

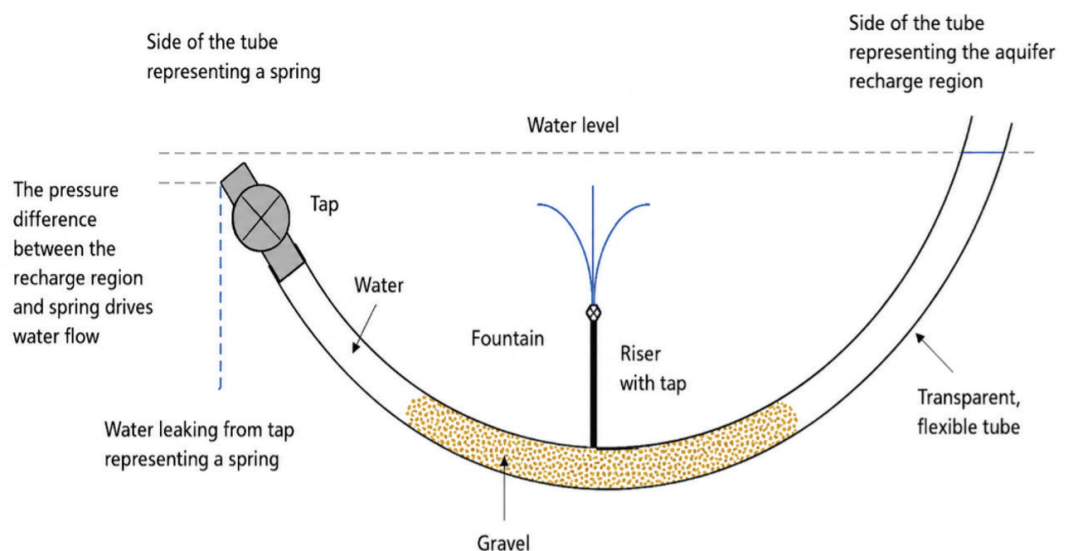
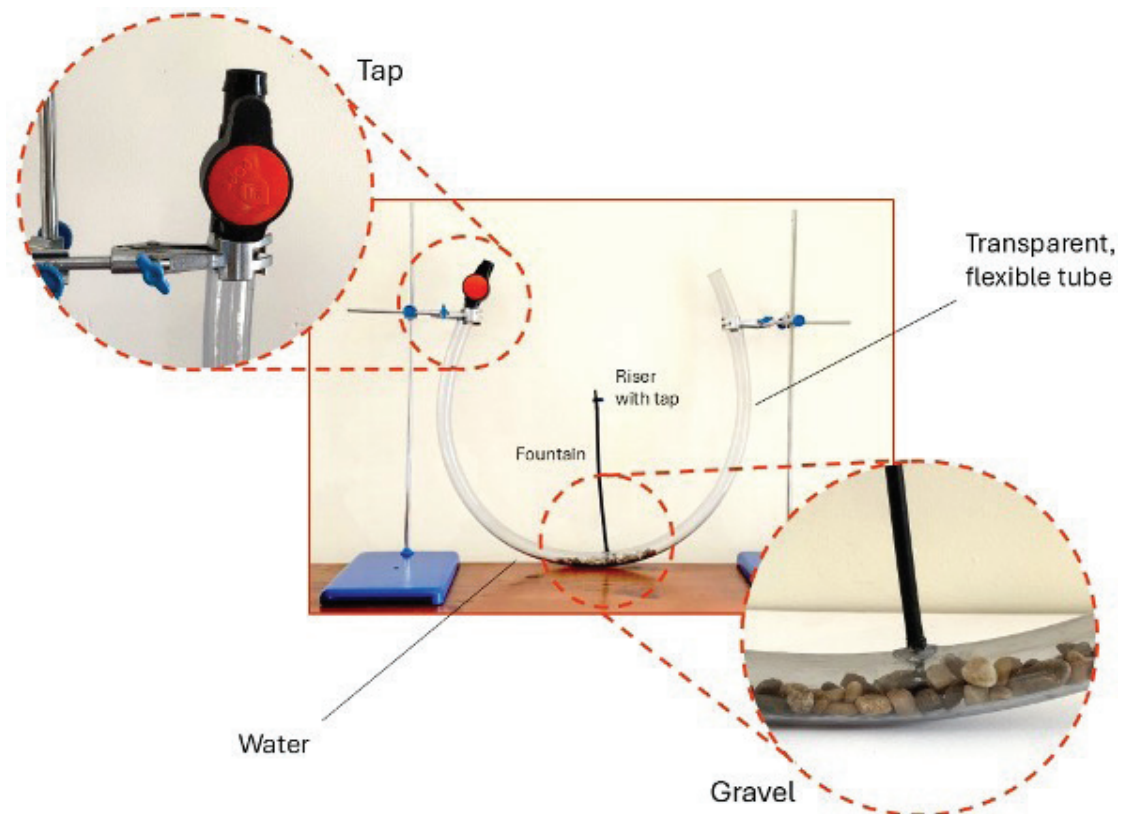


Figure 6: Experimental set-up of the physical aquifer model, showing the transparent flexible tube supported by retort stands and filled with gravel, with a central riser and tap. Enlarged views highlight the tap assembly and the gravel-filled section surrounding the riser. Photographs by Stephen Hughes; figure compiled by Ali Rad Yousefnia.



valuable for out-of-field educators, given the documented prevalence of out-of-field geography teaching in Australian schools, by providing a practical means of making groundwater processes visible while addressing relevant curriculum expectations (Kriewaldt & Lee, 2022). Table 1 summarises these curriculum connections through selected examples from the Australian Curriculum and Queensland senior secondary syllabuses.

The model consists of a length of flexible transparent tubing held at both ends with retort stands, boss heads and clamps and filled with gravel or coarse sand. A vertical riser fitted with a tap is inserted and sealed into the middle of the tube to create a controlled outlet. Transparency is essential, as it allows the relation between water and the porous medium to remain visible throughout the demonstration. Gravel commonly used in fish tanks is particularly suitable because it is clean, inexpensive, and visually effective in classroom settings, while sand may also be used where a finer-grained medium is preferred. Figure 5 shows a schematic diagram of the model, while Figure 6 presents the experimental setup in use.

Despite its simplicity, the model demonstrates several important characteristics of aquifer behaviour. First, it helps correct the common misconception that groundwater exists as an open underground body of water, such as a sea, lake, or river (Reinfried, 2006), by showing that water is stored within the pore spaces between grains of sediment. This distinction is important because terms such as “underground sea” can also imply salinity, whereas groundwater may be fresh, brackish, or saline depending on local geological and hydrological conditions. Second, it illustrates how water can move through a confined system and emerge at the surface without mechanical pumping when pressure conditions permit. In the model, this pressure results from a difference in hydraulic head, represented by the difference in water level between the two ends of the tube. If one end of the tube is raised higher than the other, the model can also demonstrate how differences in elevation generate flow towards the lower side, providing a simple analogue for spring discharge and for the relation between recharge zones and discharge points in natural systems.

The experiment is also useful in explaining the relation between hydraulic head and artesian flow. As the water level within the tube changes,

a corresponding change can be observed in the height of the water jet emerging from the tap, offering a direct visual demonstration of pressure within a confined aquifer. This creates a simple, observable link among water level, the potential energy associated with hydraulic head, and discharge behaviour. Although the physical processes governing groundwater systems are far more complex in reality, including variations in geological materials, permeability, aquifer geometry, and recharge and discharge conditions (Anderson, 2007), this U-tube configuration provides a practical introduction to the basic fluid mechanics underlying groundwater movement and pressure-driven flow. For educators, the model therefore provides a simplified representation through which these otherwise difficult-to-observe relationships can be made visible and discussed with students, reflecting the broader role of pedagogical content knowledge in transforming disciplinary knowledge into forms that can be represented, articulated, and made accessible for learning (Loughran et al., 2001; Loughran et al., 2004).

Across lower-secondary, senior secondary, and tertiary contexts, the aquifer model can be positioned through different curriculum and teaching pathways. At the lower-secondary level, the model supports Year 7 Science by making the movement of water through porous materials directly observable, while also supporting Year 7 Geography/HASS by connecting groundwater to water as a resource and to human dependence on freshwater systems. At more advanced levels, the same model can be extended to Senior Physics through pressure, flow, hydraulic head, and artesian discharge, and to university STEM contexts through modelling, sediment testing, subsurface systems, infrastructure, mining, and geothermal energy. These examples demonstrate how a single physical model can be translated from basic classroom observation into more specialised forms of scientific, technical, and applied learning.

To make the progression more explicit, Table 1 also traces how a concept such as pressure can develop across educational levels, from observing differences in water level and flow at lower-secondary level to more advanced understandings of hydraulic head, artesian pressure, and pressure-driven groundwater movement. The further pathways outlined in Table 1 show how aquifer-based teaching may also support Earth system interactions, water security, agricultural resource management, environmental governance, planning, and spatial justice. This curriculum alignment reinforces the broader argument of the paper: that aquifers can operate not only as scientific objects of study, but also as pedagogical contexts through which students

can examine physical processes, environmental understanding, and interdisciplinary learning. The physical aquifer model is one practical teaching tool within this broader argument, rather than the only educational contribution of the paper. In addition to the model, the case studies, visualisations, curriculum links, and explanatory sections discussed throughout the paper can support content development, including classroom examples and broader explanations of how aquifers influence environmental change, resource use, infrastructure, settlement patterns, and everyday life.

Conclusion and Educational Implication

Aquifers are not only complex hydrological systems, but also essential resources that sustain a substantial share of the world's fresh water and remain deeply tied to agriculture, infrastructure, energy, and environmental stability. As this paper has shown, their depletion is not a distant or purely technical issue. It has direct consequences for landscapes, settlements, and the built environment through water insecurity, land subsidence, and broader ecological stress. For this reason, aquifers should not be treated as marginal topics within Earth science alone. They need to be understood as critical real-world systems through which students can engage with the geographical and environmental challenges shaping both the present and the future.

The interdisciplinary character of aquifers also creates opportunities for collaboration across HASS and STEM teaching contexts. Their physical characteristics can be explored through porosity, pressure, recharge, groundwater flow, and Earth-system interactions, while the same systems can support geographical discussions of land use, infrastructure, governance, sustainability, environmental justice, and climate change. In a secondary-school setting, for example, Science students might use the physical model to examine groundwater storage, hydraulic head, pressure, and discharge, while Geography students investigate the same aquifer through questions of water security, resource use, environmental management, and impacts on communities. A shared activity could then bring these perspectives together, allowing students to connect what happens physically within an aquifer to decisions about how groundwater is extracted, managed, and distributed. In this way, the model and associated case studies provide more than a demonstration of groundwater behaviour; they create a practical point of connection between scientific explanation and geographical understanding.

Aquifers and their relevance to everyday life are also likely to become more important as

Table 1. Table 1 Curriculum and teaching pathways for using aquifers as an interdisciplinary HASS–STEM learning model.

Educational level/subject	Curriculum/syllabus reference or equivalent course area	Relevant topic	Main connection to the model and the topic	Translation into teaching materials	Developmental progression through the model
Year 7 Science	Australian Curriculum v9.0 Science, Year 7, AC9S7U05, together with relevant Science Inquiry processes, or equivalent lower-secondary science curriculum. Year 7 Science v9.0 curriculum alignment	Properties of materials and scientific modelling.	Shows how water behaves within a porous medium and provides an applied context for considering liquids, sediment, material properties and simplified scientific models.	Students observe water moving through gravel or sand and explain that aquifers store water within pore spaces rather than as underground lakes.	Observe and describe: students identify water storage and movement through porous material. Differences in water level and resulting flow can introduce pressure qualitatively, without requiring formal treatment of hydraulic head.
Year 7 Geography /HASS	Australian Curriculum v9.0 — Geography, Year 7, Water in the world: AC9HG7K01–K03, or equivalent lower-secondary geography/HASS curriculum. Year 7 Geography v9.0 curriculum alignment (QCAA)	Water as an environmental resource.	Connects groundwater to surface water, water movement, resource availability, sustainability and human dependence on freshwater systems. It can also support discussion of the economic, cultural and spiritual value of water, including for First Nations Australians.	Students compare rivers, lakes and aquifers, then discuss why groundwater is especially important in dry regions such as inland Australia and connect the model to examples from the GAB.	Connect process to resource: students move from observing water movement to recognising recharge, storage and discharge as parts of a wider water-resource system. Pressure remains a supporting qualitative concept explaining why groundwater can move or emerge at the surface.
Years 9–10 Geography/ HASS	Australian Curriculum v9.0 — Year 9 Geography, including AC9HG9K03–K04 on agricultural productivity, food security and management; Year 10 Geography, including AC9HG10K01, K03 and K04 on environmental change, management and sustainability. Years 7–10 Geography v9.0 Year 9 Geography curriculum alignment Year 10 Geography curriculum alignment	Water security, agriculture and environmental management.	Links the model to groundwater depletion, climate stress, agricultural production, land use, environmental change and resource governance.	Students use the model as an entry point to investigate how extraction and recharge affect communities, farming, water security, infrastructure and environmental sustainability.	Explain and apply: students connect the physical behaviour observed in the model with changes in groundwater availability. At more advanced levels, confinement and pressure can help explain why changing groundwater conditions influence discharge, while the main curriculum emphasis expands towards environmental consequences and management.

Educational level/subject	Curriculum/syllabus reference or equivalent course area	Relevant topic	Main connection to the model and the topic	Translation into teaching materials	Developmental progression through the model
Year 10 Science	Australian Curriculum v9.0 — Science, Year 10, AC9S10U04, with relevant Science inquiry processes, or equivalent upper-secondary science curriculum. Australian Curriculum v9.0 — Science (QCAA)	Earth system interactions and scientific modelling.	Positions groundwater within interactions involving the geosphere and hydrosphere and provides a physical model that can be connected to wider Earth-system and climate processes.	Students explain recharge, discharge, confinement and groundwater flow before connecting these processes to real-world aquifer systems and changing environmental conditions.	Develop systems understanding: students progress from observing flow to explaining how differences in hydraulic head can generate pressure-driven groundwater movement, while recognising that the classroom model simplifies the more complex interactions found in natural Earth systems.
Senior Physics — applied extension	QCAA Physics General senior syllabus 2025, or equivalent senior physics curriculum, used here as an applied contextual extension rather than a direct fluid-pressure syllabus requirement. QCAA Physics 2025 syllabus (QCAA)	Hydraulic head, pressure and flow as an applied physics context.	Extends the demonstration towards quantitative physical reasoning about water level, pressure differences, flow and artesian discharge.	Students compare water levels and discharge heights, investigate changes in jet behaviour and relate observations to pressure-driven flow in the model.	Move towards quantification: students can move beyond qualitative observation to relate differences in water level to hydraulic head, pressure and discharge. More advanced investigations may measure and compare head, flow or jet height.
Senior Earth & Environmental Science / Geography	QCAA Earth & Environmental Science 2025, especially Earth systems and Unit 3 renewable resources, including surface water and groundwater; QCAA Geography 2025, including local land and water management challenges. QCAA Earth & Environmental Science 2025 QCAA Geography 2025 (QCAA)	Groundwater systems, environmental risk and resource management.	Uses the GAB as a real-world case for understanding recharge, confinement, aquitards, springs, bores, groundwater availability and sustainable management.	Students interpret GAB maps and cross-sections, connect the physical model to a natural groundwater system, and investigate water security, extraction, sustainability and climate adaptation.	Apply and evaluate: students connect the model's hydraulic head and pressure relationships to a real confined aquifer, while also evaluating groundwater replenishment, extraction and sustainable management. They can explicitly examine what the physical model represents and what it cannot reproduce.

Educational level/subject	Curriculum/syllabus reference or equivalent course area	Relevant topic	Main connection to the model and the topic	Translation into teaching materials	Developmental progression through the model
Senior Agricultural Practices / Agricultural Science	QCAA Agricultural Science 2025, Unit 2: <i>Resources, Topic 1: Management of renewable resources</i> ; and relevant pathways in Agricultural Practices 2024, or equivalent agricultural/environmental science curriculum. QCAA Agricultural Science 2025 QCAA Agricultural Practices 2024 (QCAA)	Environmental considerations and renewable resource management.	Connects groundwater to freshwater availability and quality, agricultural production, drought, resource extraction, water-use efficiency and sustainable management.	Students examine how agricultural production depends on water resources and evaluate how extraction, recharge, drought, water quality and management affect long-term water security.	Evaluate resource use: students progress from understanding how groundwater moves and is replenished to assessing how groundwater availability, quality and extraction influence agricultural systems and management decisions. Pressure can be applied where artesian or bore-water supply is relevant rather than treated as the main curriculum concept.
University STEM: Design, Civil Engineering, Mechanical Engineering and Mining Engineering	Indicative university course areas or equivalent modules in engineering design, civil/geotechnical engineering, fluid mechanics, thermodynamics, mining systems, environmental engineering and subsurface systems	Modelling, pressure, groundwater flow, subsurface systems and resource extraction.	Extends the aquifer model into applied STEM contexts by linking material porosity, hydraulic pressure, fluid flow, subsurface stability, geothermal heat and extraction impacts.	Students redesign or instrument the model, test sediment types, estimate flow behaviour, relate pressure to artesian discharge, discuss aquifer compaction and land subsidence, or connect groundwater systems to mining, infrastructure and geothermal energy.	Analyse and quantify: students can investigate hydraulic head and pressure quantitatively, compare permeability and sediment behaviour, measure flow, evaluate model limitations and relate groundwater pressure changes to engineering and subsurface processes.
First-year university Geography/Planning/Built Environment	Indicative university course areas or equivalent modules in urban geography, environmental planning, sustainability, infrastructure studies, environmental governance, spatial justice and environmental humanities	Water security, infrastructure, governance and environmental justice.	Extends aquifers beyond physical science by connecting groundwater depletion to settlement, agriculture, infrastructure risk, climate adaptation and environmental justice.	Students connect the model and GAB case to water security, urban and regional development, infrastructure, resource governance, climate adaptation and unequal environmental impacts.	Integrate physical and socio-spatial understanding: students use their understanding of groundwater storage, movement and pressure as the physical basis for examining governance, infrastructure, resource competition, sustainability and environmental justice.

patterns of water demand change. Alongside familiar pressures associated with agriculture, urbanisation, and climate change, the rapid growth of digital infrastructure provides an emerging example through which students can consider new forms of resource demand. Data centres can require substantial quantities of water for cooling, although the amount varies considerably according to technology, climate, and operating conditions. A small 1 MW data centre using traditional cooling techniques has been estimated to consume approximately 25.5 million litres of water annually (Mytton, 2021), while more recent modelling suggests that direct cooling may evaporate approximately one to nine litres of water per kilowatt-hour of server energy (Privette et al., 2026). At the same time, technological developments are seeking to substantially reduce water consumption in these infrastructures (Department of Industry, Science and Resources, 2025). In Australia, data-centre capacity has also been projected to increase from approximately 1350 MW in 2024 to 3100 MW by 2030 (Lenaghan, 2025), suggesting that the relationship between digital infrastructure and resource demand warrants increasing attention.

The significance of this example is not to suggest that data centres universally depend on groundwater, but to raise awareness of an emerging form of water demand and encourage students to investigate where that water comes from and how competing demands may affect local water systems. Where groundwater forms part of a regional water supply, the classroom model provides a simple way to consider what may occur when extraction increases relative to recharge, how changes in hydraulic conditions influence groundwater movement and discharge, and why the characteristics of the aquifer matter. Geography can extend the same exercise by asking where water-intensive infrastructure is located, who else depends on the available water, how competing demands are governed, and what forms of environmental or social pressure may result. Contemporary issues such as data-centre expansion can therefore help connect the physical processes made visible by the model to wider questions of infrastructure, sustainability, and future resource management, rather than presenting aquifer education as concerned only with established forms of groundwater use.

By bringing together global cases of aquifer depletion, the Great Artesian Basin as a real-world teaching case, and a simple classroom experiment, this paper has highlighted the value of aquifers as a bridge between HASS and STEM. In this sense, aquifer education links theory to practice, makes invisible processes more legible, and connects scientific explanation to Geography, environmental change, sustainability, governance,

and environmental justice. Teaching aquifers more explicitly in geographical and environmental education can therefore do more than improve scientific understanding. It can help students think across physical and social systems, adopt more sustainable practices, and respond critically to increasingly complex environmental futures.

Acknowledgements and use of generative artificial intelligence

Generative artificial intelligence tools, including Copilot, ChatGPT, and Grammarly (embedded in Word), were used in a limited capacity during the preparation of this manuscript to support language and code refinement for map production, as well as the development and refinement of selected illustrative materials. Generative AI was also used in the production of the schematic cross-section of the Great Artesian Basin, which was subsequently reviewed, revised, and verified by the authors against the cited hydrogeological sources. The tools were used to improve clarity and readability. All scholarly content, arguments, interpretations, references, figures, and final text were reviewed, verified, and approved by the authors. The authors take full responsibility for the originality, accuracy, and integrity of the submitted manuscript.

Disclosure Statements

The authors declare no conflicts of interest.

Funding

This research received no grant from any funding agency in the public, commercial, or not-for-profit sectors.

References:

- Alam, S., Gebremichael, M., Li, R., Dozier, J., & Lettenmaier, D. P. (2019). Climate change impacts on groundwater storage in the Central Valley, California. *Climatic Change*, 157(3–4), 387–406. <https://doi.org/10.1007/s10584-019-02585-5>
- Anderson, M. P. (2007). Introducing groundwater physics. *Physics Today*, 60(5), 42–47. <https://doi.org/10.1063/1.2743123>
- Arthurs, L. A. (2019). Using student conceptions about groundwater as resources for teaching about aquifers. *Journal of Geoscience Education*, 67(2), 161–173. <https://doi.org/10.1080/10899995.2018.1561111>
- Assani, A. A., Landry, R., Azouaoui, O., Massicotte, P., & Gratton, D. (2016). Comparison of the characteristics (frequency and timing) of drought and wetness indices

- of annual mean water levels in the five North American Great Lakes. *Water Resources Management*, 30(1), 359–373. <https://doi.org/10.1007/s11269-015-1166-9>
- Australian Bureau of Statistics. (2021). *Australian statistical geography standard (ASGS) Edition 3 digital boundary files* [Data set]. <https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/latest-release>
- Australian Curriculum, Assessment and Reporting Authority. (2022). *Australian Curriculum, Version 9.0*. Australian Curriculum. <https://www.acara.edu.au/curriculum>
- Azarakhsh, Z., Azadbakht, M., & Matkan, A. (2022). Estimation, modeling, and prediction of land subsidence using Sentinel-1 time series in Tehran-Shahriar plain: A machine learning-based investigation. *Remote Sensing Applications: Society and Environment*, 25, Article 100691. <https://doi.org/10.1016/j.rsase.2021.100691>
- Bardullas, U., Félix-Anaya, C., Espejel, I., & Leyva-Figueroa, E. (2025). Climate change education in semiarid and coastal regions of Mexico: Towards an inclusive educational program. *Environmental Education Research*, 31(11), 2196–2212. <https://doi.org/10.1080/13504622.2024.2403396>
- Bioregional Assessment Program. (2016). *Great Artesian Basin boundary, subregions and cartographic mask (GABWRA)* [Data set]. <https://data.gov.au/data/dataset/241d11ac-649d-46a5-8cae-3dddb53a8010>
- Chaussard, E., Havazli, E., Fattahi, H., Cabral-Cano, E., & Solano-Rojas, D. (2021). Over a century of sinking in Mexico City: No hope for significant elevation and storage capacity recovery. *Journal of Geophysical Research: Solid Earth*, 126(4), Article e2020JB020648. <https://doi.org/10.1029/2020jb020648>
- Costigan, K. H., Kennard, M. J., Leigh, C., Sauquet, E., Datry, T., & Boulton, A. J. (2017). Flow regimes in intermittent rivers and ephemeral streams. In T. Datry, N. Bonada, & A. Boulton (Eds), *Intermittent rivers and ephemeral streams* (pp. 51–78). Academic Press. <https://doi.org/10.1016/B978-0-12-803835-2.00003-6>
- Davis, J., Kerezszy, A., & Nicol, S. (2017). Springs: Conserving perennial water is critical in arid landscapes. *Biological Conservation*, 211, 30–35. <https://doi.org/10.1016/j.biocon.2016.12.036>
- Department of Climate Change, Energy, the Environment and Water. (2025, May 20). *Great Artesian Basin*. <https://www.dcceew.gov.au/water/policy/national/great-artesian-basin>
- Department of Industry, Science and Resources. (2025, December 2). *Capture the opportunities*. <https://www.industry.gov.au/publications/national-ai-plan/capture-opportunities>
- Du, J., Laghari, Y., Wei, Y.-C., Wu, L., He, A.-L., Liu, G.-Y., Yang, H.-H., Guo, Z.-Y., & Leghari, S. J. (2024). Groundwater depletion and degradation in the North China Plain: Challenges and mitigation options. *Water*, 16(2), Article 354. <https://doi.org/10.3390/w16020354>
- Erfurt, P. (2021). *The geoheritage of hot springs*. Springer International Publishing. <https://doi.org/10.1007/978-3-030-60463-9>
- Ferguson, G., & Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change*, 2(5), 342–345. <https://doi.org/10.1038/nclimate1413>
- Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, 1(1), 51–58. <https://doi.org/10.1038/s41893-017-0006-8>
- Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). *Land subsidence in the United States* (No. 1182). U.S. Geological Survey.
- Gambolati, G., & Freeze, R. A. (1973). Mathematical simulation of the subsidence of Venice: 1. Theory. *Water Resources Research*, 9(3), 721–733. <https://doi.org/10.1029/WR009i003p00721>
- Golian, M., Saffarzadeh, A., Katibeh, H., Mahdad, M., Saadat, H., Khazaei, M., Sametazadeh, E., Ahmadi, A., Sharifi Teshnizi, E., Samadi Darafshani, M., & Dashti Barmaki, M. (2021). Consequences of groundwater overexploitation on land subsidence in Fars Province of Iran and its mitigation management programme. *Water and Environment Journal*, 35(3), 975–985. <https://doi.org/10.1111/wej.12688>
- Gong, H., Pan, Y., Zheng, L., Li, X., Zhu, L., Zhang, C., Huang, Z., Li, Z., Wang, H., & Zhou, C. (2018). Long-term groundwater storage changes and land subsidence development in the North China Plain (1971–2015). *Hydrogeology Journal*, 26(5), 1417–1427. <https://doi.org/10.1007/s10040-018-1768-4>
- Gupta, D. (2023). Free power, irrigation, and groundwater depletion: Impact of farm electricity policy of Punjab, India. *Agricultural*

- Economics*, 54(4), 515–541. <https://doi.org/10.1111/agec.12773>
- Habermehl, M. A. (2020). Hydrogeological overview of springs in the Great Artesian Basin. *The Proceedings of the Royal Society of Queensland*, 126, 29–46. <https://doi.org/10.5962/p.357836>
- Haghighi, M. H., & Motagh, M. (2019). Ground surface response to continuous compaction of aquifer system in Tehran, Iran: Results from a long-term multi-sensor InSAR analysis. *Remote Sensing of Environment*, 221, 534–550. <https://doi.org/10.1016/j.rse.2018.11.003>
- Harrington, G. A., Gardner, W. P., Smerdon, B. D., & Hendry, M. J. (2013). Palaeohydrogeological insights from natural tracer profiles in aquitard porewater, Great Artesian Basin, Australia. *Water Resources Research*, 49(7), 4054–4070. <https://doi.org/10.1002/wrcr.20327>
- Harrison, A. G., & Treagust, D. F. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics*, 98(8), 420–429. <https://doi.org/10.1111/j.1949-8594.1998.tb17434.x>
- Helm, D. C. (1975). One-dimensional simulation of aquifer system compaction near Pixley, California: 1. Constant parameters. *Water Resources Research*, 11(3), 465–478. <https://doi.org/10.1029/WR011i003p00465>
- Hoffmann, J., Zebker, H. A., Galloway, D. L., & Amelung, F. (2001). Seasonal subsidence and rebound in Las Vegas Valley, Nevada, observed by Synthetic Aperture Radar Interferometry. *Water Resources Research*, 37(6), 1551–1566. <https://doi.org/10.1029/2000WR900404>
- Huddleston-Holmes, C. (2014). *Geothermal energy in Australia*. CSIRO.
- International Water Management Institute. (2026). *Country strategic roadmap: India 2024–2030*. <https://doi.org/10.5337/2026.212>
- Jones, C., Stanton, D., Hamer, N., Denner, S., Singh, K., Flook, S., & Dyring, M. (2020). Field investigation of potential terrestrial groundwater-dependent ecosystems within Australia's Great Artesian Basin. *Hydrogeology Journal*, 28(1), 237–261. <https://doi.org/10.1007/s10040-019-02081-1>
- Kriewaldt, J., & Lee, S. J. (2022). Tracking the extent of out-of-field teaching of geography: Issues and implications for advancing school geography. *Geographical Education (Online)*, 35, 46–51.
- Lenaghan, N. (2025, March 12). The AI surge: 175 new data centres and \$26b in investment. *Australian Financial Review*. <https://www.afr.com/property/commercial/the-ai-surge-175-new-data-centres-and-26b-in-investment-20250311-p5lisk>
- Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology*, 29(5), 763–771. <https://doi.org/10.1007/s10980-014-0034-y>
- Loughran, J., Milroy, P., Berry, A., Gunstone, R., & Mulhall, P. (2001). Documenting science teachers' pedagogical content knowledge through PaP-eRs. *Research in Science Education*, 31(2), 289–307. <https://doi.org/10.1023/A:1013124409567>
- Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching*, 41(4), 370–391. <https://doi.org/10.1002/tea.20007>
- Mishra, V., Dangar, S., Tiwari, V. M., Lall, U., & Wada, Y. (2024). Summer monsoon drying accelerates India's groundwater depletion under climate change. *Earth's Future*, 12(8), Article e2024EF004516. <https://doi.org/10.1029/2024EF004516>
- Moggridge, B. J. (2020). Aboriginal people and groundwater. *The Proceedings of the Royal Society of Queensland*, 126, 11–27.
- Motagh, M., Walter, T. R., Sharifi, M. A., Fielding, E., Schenk, A., Anderssohn, J., & Zschau, J. (2008). Land subsidence in Iran caused by widespread water reservoir overexploitation. *Geophysical Research Letters*, 35(16), Article L16403. <https://doi.org/10.1029/2008GL033814>
- Mytton, D. (2021). Data centre water consumption. *Npj Clean Water*, 4. <https://doi.org/10.1038/s41545-021-00101-w>
- Natural Earth. (n.d.). *Natural Earth: Free vector and raster map data* [Data set]. Retrieved <https://www.naturalearthdata.com/>
- Oh, P. S., & Oh, S. J. (2011). What teachers of science need to know about models: An overview. *International Journal of Science Education*, 33(8), 1109–1130. <https://doi.org/10.1080/09500693.2010.502191>
- Pointet, T. (2022). The United Nations World Water Development Report 2022 on groundwater: A synthesis. *LHB*, 108(1), Article 2090867. <https://doi.org/10.1080/27678490.2022.2090867>
- Privette, A. P., Barros, A., & Cai, X. (2026). Data centers water footprint: The need for more transparency. *AGU Advances*,

- 7(2), Article e2025AV002140. <https://doi.org/10.1029/2025AV002140>
- Queensland Curriculum and Assessment Authority. (2024). *Earth & environmental Science 2025* [General senior syllabus]. <https://www.qcaa.qld.edu.au/senior/senior-subjects/syllabuses/sciences/earth-environmental-science>
- Radke, B., Ferguson, J., Cresswell, R., Ransley, T., & Habermehl, M. (2000). Hydrochemistry and implied hydrodynamics of the Cadnawowie–Hooray Aquifer, Great Artesian Basin, Australia. *Bureau of Rural Sciences, Canberra*, 40.
- Reinfried, S. (2006). Conceptual change in physical geography and environmental sciences through mental model building: The example of groundwater. *International Research in Geographical and Environmental Education*, 15(1), 41–61. <https://doi.org/10.2167/irgee186.0>
- Rizvi, S. F., Izhar, S. K., Shahab, A., Kuddus, M., & Roohi, R. (2025). Comprehensive review on groundwater exploitation, depletion, and its management: Sustainable approach toward agricultural productivity in India. *Environmental Quality Management*, 34(4), Article e70092. <https://doi.org/10.1002/tqem.70092>
- Rossini, R. A., Arthington, A. H., Jackson, S. E., Tomlinson, M., Walton, C. S., & Flook, S. C. (2020). Springs of the Great Artesian Basin—Knowledge gaps and future directions for research, management and conservation. *The Proceedings of the Royal Society of Queensland*, 126, 305–321.
- Sharma, M., & Apoorva. (2025). Water security in Australia. In K. D. Bahukhandi, D. P. Panday, & T. G. G. Chaminda (Eds.), *Water scarcity management* (1st edn, pp. 71–98). Wiley. <https://doi.org/10.1002/9781394176748.ch5>
- Sobti, M. P., & Rad Yousefnia, A. (2024). Beyond water: Step wells and community hydraulics in modern India. In A. Cheshmehzangi, M. Sedrez, & A. Flynn (Eds.), *Rethinking stormwater management through sustainable urban design* (pp. 273–292). Springer Nature. https://doi.org/10.1007/978-981-97-4924-9_14
- Tabari, M. M. R., & Eilbeigi, M. (2025). Evaluating and determining the mechanism of land subsidence susceptibility under excessive overexploitation of groundwater and problematic sediments. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-025-06977-9>
- Takagi, H., Esteban, M., Mikami, T., Pratama, M. B., Valenzuela, V. P. B., & Avelino, J. E. (2021). People's perception of land subsidence, floods, and their connection: A note based on recent surveys in a sinking coastal community in Jakarta. *Ocean & Coastal Management*, 211, Article 105753. <https://doi.org/10.1016/j.ocecoaman.2021.105753>
- Taylor, N. A., Taylor, E. A., Maloney, S. K., & de Dear, R. J. (2022). Contributions from a land down under: The arid continent. In *Thermal physiology: A worldwide history* (pp. 357–404). Springer.
- Terzaghi, K. (1925). Principles of soil mechanics. IV. Settlement and consolidation of clay. *Engineering News-Record*, 95(22), 874–878.
- Touchart, L. (2012). Baikal, Lake. In L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of lakes and reservoirs* (pp. 83–91). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_50
- United Nations Department of Economic and Social Affairs. (2019). *World urbanization prospects: The 2018 revision*. United Nations. <https://doi.org/10.18356/b9e995fe-en>
- United Nations Department of Economic and Social Affairs. (2026). *The Sustainable Development Goals report 2026*. United Nations. <https://unstats.un.org/sdgs/report/2026/>
- Wittfogel, K. A. (1957). *Oriental despotism: A comparative study of total power*. Yale University Press.
- Wu, W.-Y., Lo, M.-H., Wada, Y., Famiglietti, J. S., Reager, J. T., Yeh, P. J.-F., Ducharne, A., & Yang, Z.-L. (2020). Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nature Communications*, 11(1), Article 3710. <https://doi.org/10.1038/s41467-020-17581-y>
- Zahnow, R., Rad Yousefnia, A., Hassankhani, M., & Cheshmehzangi, A. (2025). Climate change inequalities: A systematic review of disparities in access to mitigation and adaptation measures. *Environmental Science & Policy*, 165, Article 104021. <https://doi.org/10.1016/j.envsci.2025.104021>