Humans, water, and the colonization of Australia

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The Pleistocene global dispersal of modern humans required the transit of arid and semiarid regions where the distribution of potable water provided a primary constraint on dispersal pathways. Here, we provide a spatially explicit continental-scale assessment of the opportunities for Pleistocene human occupation of Australia, the driest inhabited continent on Earth. We establish the location and connectedness of persistent water in the landscape using the Australian Water Observations from Space dataset combined with the distribution of small permanent water bodies (springs, gnammas, native wells, waterholes, and rockholes). Results demonstrate a high degree of directed landscape connectivity during wet periods and a high density of permanent water points widely but unevenly distributed across the continental interior. A connected network representing the least-cost distance between water bodies and graded according to terrain cost shows that 84% of archaeological sites >30,000 y old are within 20 km of modern permanent water. We further show that multiple, well-watered routes into the semiarid and arid continental interior were available throughout the period of early human occupation. Depletion of high-ranked resources over time in these paleohydrological corridors potentially drove a wave of dispersal farther along well-watered routes to patches with higher foraging returns.

Sahul | Pleistocene colonization | radiocarbon | human dispersal | paleohydrological corridor

Considerable debate has surrounded the timing, routes, and mechanisms of early human colonization of the continent of Australia. Initial occupation from the north appears to have begun before 47 kyBP (1–8) with relatively rapid movement therafter; for example, the Willandra Lakes region in the southeast of the continent may have been occupied within 1,000 y after the arrival of humans (1, 9, 10). Birdsell (11) considered that dispersal occurred rapidly and throughout the continent, whereas Bowdler (12) considered that early dispersal took place along the coastlines, with limited initial occupation of the interior. Horton (13) and Tindale (14) added the postulates that, upon arrival in the northwest, or north, respectively, humans dispersed through the northern and eastern interior woodlands along riverine corridors and thence to the coast. These "end-member" dispersal scenarios (Fig. 1) subsequently have been reworked to include a more nuanced understanding of "the filling of the continent" (p. 453 in ref. 15) as variably dependent on a matrix of biogeographic (16), ecological/climatic (17), and sociological/technological (18, 19) facilitators of—or barriers to—dispersal from an initial point of entry in the north (20). The vast interior of the continent is now viewed as a mosaic of potential oases, corridors, and barriers, with the viability of a specific region for occupation or transit also depending on the trajectories of environmental change (21–24).

O'Connell and Allen (1), building on previous work (25) and drawing on optimal foraging theory, propose a model of human dispersal throughout the continental interior driven by resource availability/depletion, with the major interior rivers/river basins representing the environments most attractive to human foragers; these environments extended into other areas for short periods, at times of rain-related resource "flushes." Smith (26) attributes human dispersal through the desert to access to the food resources provided by stepping stones of small and variable water features, rather than to the resources themselves. All treatments of human dispersal in Pleistocene Sahul to date have lacked an explicit spatial dimension. What potential dispersal routes were available, where, and under what circumstances? These questions relate specifically to water in the landscape, because water is critical for human survival (27–30), and three-quarters of Australia is semiarid or arid. In the absence of spatial information, discussion of the patterns of human colonization in Australia usually have been framed in general terms of aridity—the absence of water—although it is well known that even the driest deserts in Australia are periodically flooded (21, 31, 32). In the Western Desert, for example, Peterson (p. 65 in ref. 33) noted that "after substantial falls of rain the population disperses widely to the most ephemeral sources far out on the plains. As the water supplies disappear the people retreat back to the more permanent water supplies, where they may become trapped for a period" (34). It is perhaps for this reason that Gould (35) observed that indigenous Australians prioritize foraging near satellite water holes before settling closer to the main water hole. In the Western Desert, Veth (36) notes a positive correlation between the number of extractive artifacts and the permanency of water.

Aridity in isolation therefore is not necessarily a barrier either to habitation or to transit. It is the duration of inundation, the connectedness of water at times of inundation, and the location of permanent water in the landscape that dictates where, and for what length of time, humans could reside in or transit through most of interior Australia. O'Connell and Allen note that "terrestrial patch rank was determined primarily by the availability of freshwater, as measured by the volume and reliability of precipitation and/or local stream flow" (pp.7–8 in ref. 25).

The Water Observations from Space (WOfS) dataset (37) allows an assessment of the spatial distribution and permanency of standing

Significance

Australia is the driest inhabited continent on earth, but humans dispersed rapidly through much of the arid continental interior after their arrival more than 47,000 y ago. The distribution and connectedness of water across the continent, and particularly in its arid core, played a pivotal role in facilitating and focusing early human dispersal throughout the continent. We analyze the distribution and connectedness of modern permanent water across Australia. The modelled least-cost pathways between permanent water sources indicate that the observed rapid occupation of the continental interior was possible along multiple, well-watered routes and likely was driven by the depletion of high-ranked resources in each newly occupied area over time.

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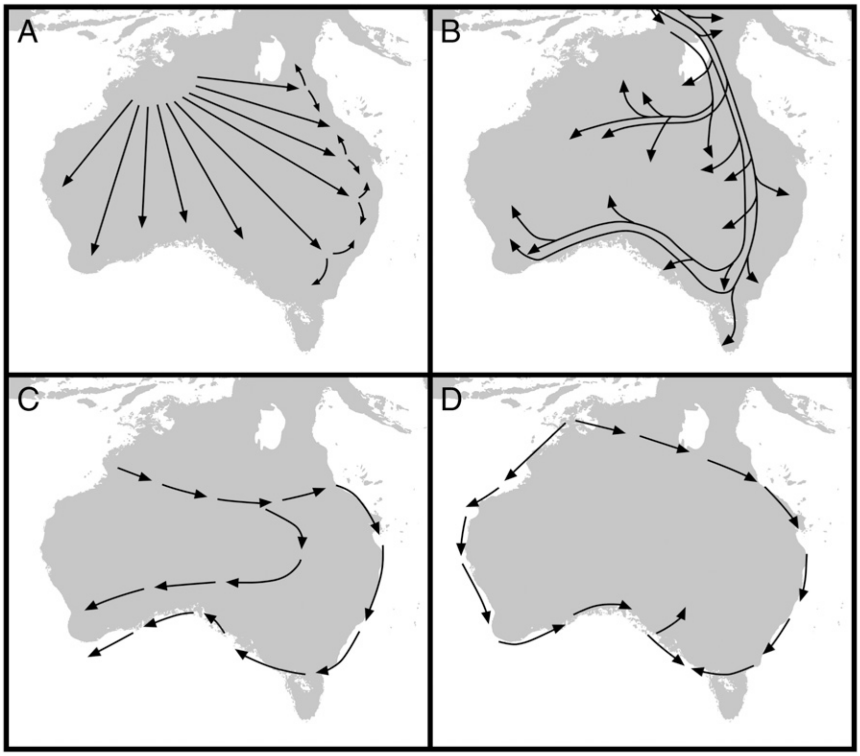

Fig. 1. Proposed colonization models for the Australian continent. (*A*) Birdsell (11). (*B*) Tindale (14). (*C*) Horton (13). (*D*) Bowdler (12).

water in the modern Australian landscape. Here we use this information, coupled with the distribution of small natural permanent water bodies (springs, gnammas, native wells, waterholes, and rockholes) compiled from the 1:250,000 topographic sheets (nationalmap.gov.au) to provide a spatially explicit assessment of the opportunities for Pleistocene human occupation of, and dispersal throughout, Australia. A connected network was produced representing the least-cost distance between water bodies and graded according to terrain cost.

Results and Discussion

The results of the spatial analysis of the 112,786 individual natural water points (Dataset S1) demonstrate a high degree of directed landscape connectivity during wet periods and a high density of water points distributed widely but unevenly across modern arid and semiarid Australia (Fig. S1). Inundation events may have been both more and less common in the past, permanent water points may have shifted location in the past, some permanent water may not be potable, and small isolated water points may not have been readily accessible to parties unfamiliar with the area into which populations were moving. Nevertheless, the broad-scale patterns observable in the present are likely to have held in the past and particularly during the wetter periods of initial human dispersal. All the archaeological sites from >30 ka are closely associated with the least-cost pathways identified in Fig. 2 on the basis of modern permanent water distribution.

This assertion is supported by the close proximity of the archaeological sites from >30 ka to modern permanent water (Fig. 3). Excluding four sites in the Willandra Lakes area that were within 10 km of water at the time of initial occupation but now are >50 km from permanent water because of the avulsion of the Lachlan River (38), 84% of the sites from >30 ka (46 of 55 sites) are <20 km, or approximately a day's walk, from modern permanent water, and all sites are <40 km, or a 2-d walk. This relationship is stronger than that between younger archaeological sites and water (65% <20 km), including sites dating to the Holocene when climate and the distribution of permanent water were similar to the present day (39). Archaeological sites in Australia are frequently located and investigated as a result of linear infrastructure surveys associated with mining, road, and pipeline developments and as such are not biased per se toward locations associated with water. Research-based probabilistic survey is extremely rare in Australia. The explicit comparison between archaeological sites is important because it further diminishes potential bias associated with site selection, given that all sites were discovered by broadly the same array of archaeological survey techniques.

The distribution of sites from <30 ka is similar to the distribution of land area relative to modern permanent water (Fig. 3), with 65% of 1,049 sites <20 km and 20% of sites >40 km from modern permanent water. This distribution suggests that more recent populations have developed the ability to journey farther from permanent water than populations could during the initial dispersal. The association between archaeological sites from >30 ka and modern permanent water suggests that the distribution of modern permanent water is a reasonable analog for the distribution of permanent water in the past.

At the continental scale it is clear that dispersal over long distances was rapid, implying the existence of connected and relatively abundant resources, including water. Initial colonization certainly had occurred by 47 ka (1) but may have occurred earlier (50–55 ka; e.g., ref. 3). From an initial entry point in the northwest or north (see ref. 20 for a review), the Willandra Lakes region in southeast Australia was occupied by 41–45 ka (1) or 46–50 ka (9), and Devil's Lair in the southwest was occupied by 43–48 ka (1) or by ~50 ka (40). There was a lag in occupation of the arid bedrock core of the continent, which was not occupied until 36.5–42.5 ka (23). These data imply a maximum dispersal interval of ~5,000–10,000 y, during which most of the readily habitable parts of the continent were occupied.

The analysis presented in Fig. 2 cannot confirm or rule out any of the extant models of human dispersal through Australia after arrival but does allow several robust inferences (Fig. 4).

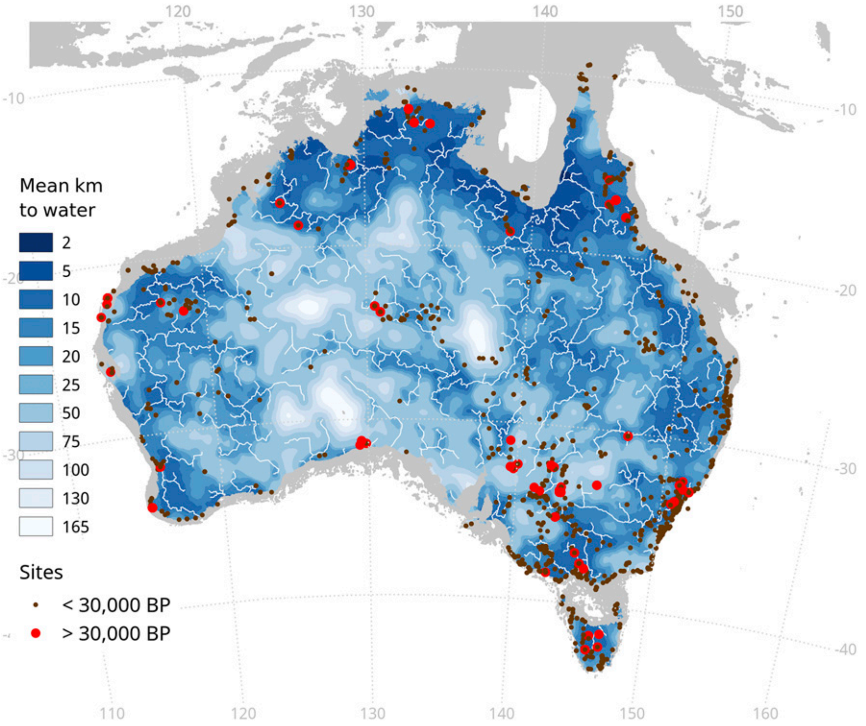

Fig. 2. Distance to water and connectivity lines calculated with a topographic convergence index of the travel-cost surface with a minimum catchment size of ~350 km^2 (see *Materials and Methods*). Small black and larger red dots represent archaeological sites from <30 ka and >30 ka, respectively.

A strictly coastal route from a point of entry in the northwest (20) to the south and then east is possible, but such a western coastal route, thence up the Murray-Darling River to Willandra Lakes (for example) would be at a minimum five times longer than an overland route across the north of the continent and south through Queensland (and would be even longer at times of lowered sea level).

Immediate and rapid continent-wide dispersal (11) is unlikely, because there are large regions where, at any time, accessible permanent water is very limited and the distance between permanent water points is long; for example, ~818,000 km^2 of land (~11% of the total mainland area), mostly in the center and west of the continent (Fig. 3), is >50 km from permanent water (Fig. 2). A "woodland" route (13) from the northwest, initially east across the monsoon savannas to Lake Carpentaria and turning south through Western Queensland to the Lake Mungo region and central South Australia would have been relatively well-watered, as would an interior route south from an initial entry point in the north (14). From the Gulf of Carpentaria south, multiple paleohydrological corridors [*sensu* Breeze et al. (30)] through interior Queensland existed following abundant, permanent water points <20 km apart that would be directly connected at times of inundation. This connectivity would facilitate ready dispersal by hunter-gatherers with an average daily foraging range of 10–15 km (41, 42). These same regions also likely contained attendant, abundant food resources and focused populations of obligate drinking fauna. Depletion of high-ranked resources in these patches over time would drive a wave of dispersal farther along well-watered routes to patches with higher foraging returns (1, 25).

A lag in the occupation of central Australia amounting to ~10,000 y suggests that the arid interior was relatively difficult to access. The bedrock-dominated core of the continent was mostly readily accessible (Fig. 2), although with greater difficulty and likely only during extended wet periods, via (*i*) well-connected water points in southwest Queensland or South Australia (along the Finke River) or (*ii*) relatively well-connected permanent water points south through the central Northern Territory. Although multiple archaeological sites are known along the more southerly routes, none are known along the putative northern route, suggesting that the southern route is more likely to have been the one followed.

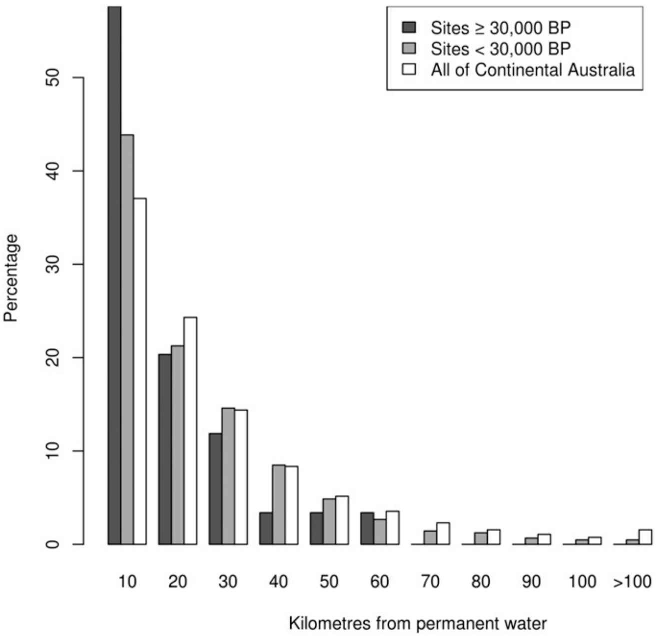

Fig. 3. Percentage of archaeological sites and land area as a function of the maximum distance to modern permanent water. Note that all archaeological sites in the >30 ka category that are 50 km or more from modern permanent water are in the Willandra Lakes region (see text).

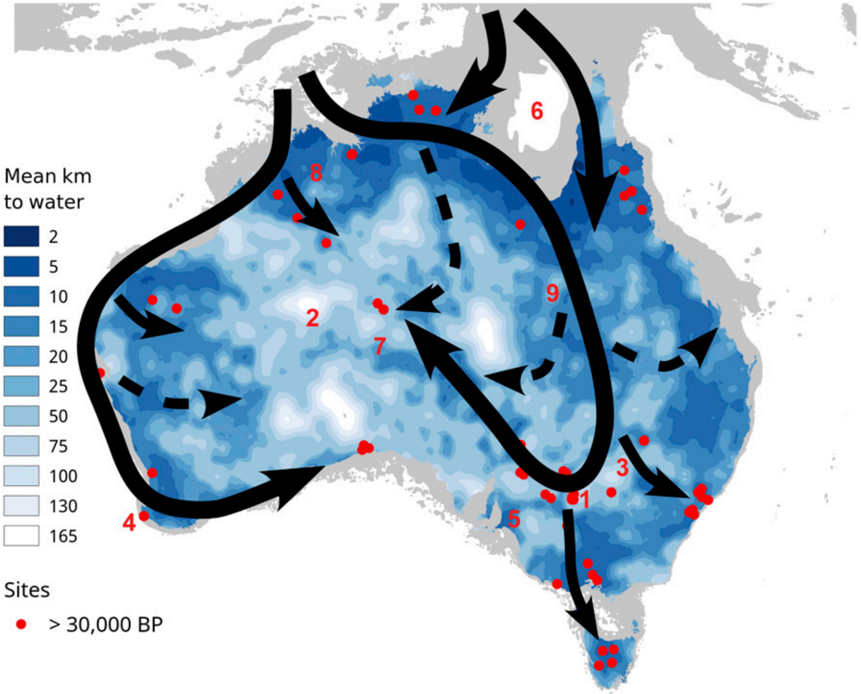

Fig. 4. Hypothesized pathways for colonization of the Australian continent based on the distance to water and the travel-cost surface (see the legend of Fig. 2 and *Materials and Methods*). Locations mentioned in the text are numbered: (1) Willandra Lakes; (2) Western Desert; (3) Lachlan River; (4) Devil's Lair; (5) Murray-Darling River; (6) Lake Carpentaria; (7) Finke River; (8) Kimberley; and (9) Channel Country.

As the continent dried during the Last Glacial Maximum, populations contracted into smaller areas with access to a reduced number of permanent water points and reduced food resources. Rather than continental-scale refuges (16, 43, 44), these areas may have been a patchwork of smaller, individually isolated refugia (45, 46) distributed more broadly across the continent. A higher density of these isolated refugial areas occurred in regions such as the Kimberley, the rocky central arid zone, and the Channel Country, all areas identified as regional refugia by Williams et al. (43) on the basis of the distribution of dated archaeological sites, as well as in some wetter coastal areas (46). Refugial areas, particularly those located in the sandy deserts fringing the arid bedrock core of the continent, may well have been separated by truly uninhabited regions.

Interpretations of the analysis presented above are subject to three caveats. First, the spatial analytical results are derived from the modern distribution of permanent water points in the landscape. Of course, it is likely that substantially less water was available across the continent at some times in the past and particularly during the Last Glacial Maximum (47, 48). However, during the millennia following human arrival, the hydroclimate at the continental scale cycled several times through conditions similar to modern conditions, toward both wetter and drier periods, potentially with different timing and to differing degrees from the south to the north of the continent (48–51). Hence the modern distribution of water is likely to be broadly analogous to the situation at some times during early dispersal, and at the continental scale the connectivity of water points also is likely, in a relative sense, to have been similar in the past.

Second, some small permanent water points, such as springs, which are known to be important to human populations, occur widely in arid and semiarid Australia but are not necessarily connected to major inundation pathways (52–55). Although it is possible that springs in local areas will activate or deactivate over time and that billabongs and other small water sources in bedrock (gnammas, rockholes) will form and disappear over time, the areas where such features have been located in the past can be assumed to be relatively constant, because they require particular lithologies, hydrogeological environments, and/or geomorphic settings. Hence their modern distribution is likely broadly comparable to their distribution in the past, with many such locations being important refugia as a result of their long-term stability (56–58). In the context of early human dispersal, small isolated water points (identified from topographic sheets) are likely to have been less significant than areas connected during times of inundation (identified by the WOfS data), because of the risk associated with striking out into an unknown area across an intervening landscape with no known water points. Many of the small isolated water points, actively maintained in pre-European times to allow permanent habitation in arid regions (55), would not have been available to a party traversing new country except at times of significant inundation.

Third, we assume that the gross routing of floodwaters at the continental scale is unlikely to have changed dramatically in the last 50,000 y, except locally in response to geomorphic changes as a result of neotectonism (59). Most of Australia is tectonically stable; however, the drying of Willandra Lakes since the Last Glacial Maximum (38) represents one example in which a well-watered region containing evidence of occupation before 30 ka (1, 9) is significantly (>50 km) farther from permanent water now than during initial human occupation.

Conclusions

The location and connectivity of water in the landscape is critical to understanding early human dispersal through water-limited environments across the globe (27, 28). These considerations are particularly important for Pleistocene Australia, given the broad extent of semiarid and arid environments and the comparative rapidity with which these areas were colonized. The clear relationship between archaeological sites from >30 ka and modern permanent water provides strong evidence that, at the continental scale, these factors have always been important. A striking feature of the spatial analysis presented here is the clear linkage of well-watered routes from northern Australia, through the eastern semiarid and arid zone, to southeastern Australia and into the rocky arid center of the continent. Given that permanent water points act as a focus for potential prey and other resources, the apparently rapid dispersal through much of interior Australia likely was similarly focused along these well-connected routes defined by permanent water points, and dispersal potentially was driven farther along these routes by the progressive depletion of local resources. A corollary of this analysis is that some apparently well-watered, interconnected regions lie along potential dispersal routes but have yet to yield evidence of early (or, in some places, any) occupation in prehistory. These regions include the Channel Country of southwest Queensland and the route identified in this study that runs south through the Northern Territory into the arid center (Fig. 4). The lack of evidence of early occupation could result from poor preservation potential, from limited archaeological survey effort, or from the identified route indeed not being used. These alternatives, in turn, suggest that the dataset, in combination with other terrain attributes, can be used predictively to identify areas worthy of investigation for their potential to yield previously unrecognized archaeological sites to delimit the initial dispersal routes better.

The approach presented here represents a progression from abstract ideas regarding the filling of the continent to testable hypotheses grounded in spatially explicit data (Figs. 2 and 4). The analysis suggests that permanent water, connected during periodic inundation events, provided—and provides—effective conduits for human movement over thousands of kilometers through much, but not all, of the continental interior. The WOfS dataset only currently covers the Australian continent. However, it is based on satellite imagery with global coverage. The imagery can be used to derive similar products elsewhere, in turn enabling progression beyond the identification of drainage networks and basins as potential dispersal routes (29, 30, 60) to a more nuanced interpretation that considers the permanency of water across a landscape. The same approach therefore can be used to develop and test models that seek to explain the rapid dispersal of modern humans out of Africa (27–30, 61) via similar periodically interconnected hydro-ecological networks (1, 27, 28, 43, 62).

Materials and Methods

Data Sources. The WOfS dataset was created by Geoscience Australia (GA), the Australian Government's agency responsible for geospatial research and information. The data were derived by the application of an algorithm, developed in-house by GA, to determine the presence of water in Landsat-5 and Landsat-7 imagery. The Landsat satellites have a repeat orbit path of 16 d, and the imagery from which WOfS was derived dates from 1987. The results come in the form of a number of derivatives, each with a 30-m spatial resolution, representing the number of clear observations made, the number of occasions on which water was detected, the percentage of clear observations in which water was detected, and the confidence that a water observation in the particular location is correct (37). One mode presents the percentage of clear observations in which water was detected, filtered using the confidence layer; we used that dataset for the current method and visually checked the observations to remove permanent water bodies resulting from either dams or water bores.

A measure of ancient human presence across Australia is provided by radiocarbon dates from archaeological sites. This information has been compiled in the Austarch database comprising 5,044 radiocarbon dates from 1,748 sites and a further 450 (dominantly luminescence) dates from 86 sites (63).

Spatial Analysis. A connected network was produced, representing the least-cost distance between water bodies and graded according to terrain cost.

Water Bodies. The tiled WOfS data, the values of which represent the percentage of observations over 30 y in which each pixel was identified as water, were merged into one surface and converted to a binary raster representing the presence of water bodies, having been filtered for values greater than 90% observed water.

To this water body data were added features from the Australian Hydrological Geospatial Fabric (Geofabric) database, which is made available for download by the Australian Government Bureau of Meteorology (www.bom.gov.au/water). The dataset contains the location of water features coded as spring, gnamma hole, native well, pool, rockhole, soak, water tank, bay, and water hole. The data were filtered for features that were not bay or water tank.

The two datasets were merged by first converting them from point vector to binary raster layers with a spatial resolution of 1 minute (~1,850 m) and then combining them with a logical OR operator to mitigate the duplication of point data at the working scale.

Minimum-Cost Connectivity. A cost surface was calculated by which the optimal routes between water bodies could be determined. This surface takes two factors into account: the relative distance of a cell to the nearest water body and the difficulty of passing through that cell. The latter consideration is one of horizontal distance and (in this simplified model) slope. With uniform pixel sizes, horizontal distance is similar for each cell. For a slope factor, Tobler's Hiking Function (64) was used to determine a slope cost as the ratio of walking speed with zero slope to that at the slope of each cell.

Slope in each cell was calculated using the 1-second hydrologically enforced digital elevation model derived by Geoscience Australia from the Satellite Radar Topography Mission dataset (65). From this model, the terrain cost surface was calculated as described. The final surface was calculated as the cumulative cost of moving from each cell to the nearest water body. With the results of this calculation serving as a quasi-topographical surface, we used a least-cost search algorithm (66) within the r.watershed function of GRASS GIS (67) to trace least-cost routes from any part of modern Australia to any part of the coast, which has a cost of zero. The cost surface is analogous to an elevation model, in which high values drain toward lower values such as the coast or water holes. Routes out of local minima such as water holes are established by filling the surrounding basin until it spills over a sill at a certain threshold. This process is repeated until the streams reach the coastline. In principle, each pixel can have its streamflow path mapped; therefore, for analysis purposes, it is necessary to decide on a minimum basin size governing the density or the strength of the mapped streams. A basin size of 100 pixels (~350 km^2) was used for our output.

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