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Title of Article:

Terrestrial freshwater lenses: Unexplored subterranean oases

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Abstract

Freshwater lenses are lenticular bodies of fresh groundwater that develop above more saline groundwater within the same host aquifer due in part to buoyancy. In contrast to the widely studied situation of freshwater lenses in coastal aquifers, the formation, location and persistence of freshwater lenses in terrestrial settings are poorly understood. This is despite inland aquifers commonly containing saline groundwater, particularly in arid and semi-arid climates, and the local occurrences of freshwater being critical for ecosystems and human endeavour. We identify and classify known terrestrial freshwater lenses (TFLs) using four formation categories, namely topography, geology, groundwater-surface water interaction and recharge mechanisms. The resulting typology highlights the importance of buoyancy in the formation of TFLs in otherwise unlikely situations, implying that TFLs may be more prevalent than previously thought. TFLs represent some of the most vulnerable and precious freshwater resources on Earth that require considerably more research into mechanisms of formation and threats to their existence.

Keywords

1. saline groundwater
2. terrestrial freshwater lens
3. density
4. water resources
5. typology
6. review

1. Introduction

With increasing global population, our dependence on groundwater for both food production and drinking water is escalating [*Oki and Kanae*, 2006; *Ercin and Hoekstra*, 2014]. Moreover, two thirds of humankind inhabit regions that experience severe water scarcity for at least one month of the year [*Vörösmarty et al.*, 2000]. Consequently, the discovery, exploitation and management of fresh (TDS < 1000 mg/L) groundwater resources in water-limited regions are critically important. In some regions, fresh groundwater exists as a lens; a lenticular-shaped body of freshwater that persists within otherwise saline aquifers due to freshwater-saltwater density contrasts, which inhibit mixing [*Drabbe and Badon Ghyben*, 1889; *Herzberg*, 1901]. Freshwater lenses locally support human and ecosystem functions in both coastal and non-coastal ('terrestrial') settings [*Bauer et al.*, 2006; *Cendón et al.*, 2010]. However, in contrast to the significant body of work on coastal freshwater lenses [*Arnow*, 1954; *Underwood et al.*, 1992; *Stuyfzand*, 1993; *Bailey et al.*, 2009], the current understanding of terrestrial freshwater lenses (TFLs) is limited. In particular, the presence and origins of TFLs are often unclear and/or unintuitive [*Milewski et al.*, 2014; *Werner and Laattoe*, 2016] relative to analogous coastal freshwater lenses.

Freshwater lenses in coastal aquifers and oceanic islands are the result of rainfall infiltration that accumulates above saline groundwater derived from the sea [*Arnow*, 1954]. Saline groundwater is also common inland, where it is widespread at shallow to intermediate depths due to the presence of remnant marine water [*El-Sayed et al.*, 1991], dissolution of evaporite deposits [*Kloppmann et al.*, 2001], and/or evapotranspiration of rainwater [*Cartwright et al.*, 2004]. The last process predominates in rainfall-limited climates. In contrast to the more widely studied surface oases that are also mostly groundwater-derived [*Fitzsimmons et al.*, 2005; *Silcock*, 2010], TFLs are less detectable subterranean oases that are at least partially shielded from evaporative losses, and that coexist with saline groundwater. Figure 1 identifies large bodies (>10^9 m^3) of known terrestrial saline (>1000 mg/L) groundwater at depths of <500 m, as identified by the UNESCO International Groundwater Resources Assessment Centre [*Van Weert et al.*, 2009]. In Figure 1, saline groundwater in peninsulas and islands of the north-western Pacific margin and Southeast Asia is formed from a combination of terrestrial and marine processes; otherwise, saline groundwater of modern marine origins is omitted. The occurrence of TFLs requires at least intermittent infiltration of freshwater, although the processes that lead to TFLs and their persistence are unclear due to the small number of prior TFL studies. The current view is that TFLs are quite rare [*Houben et al.*, 2014]. However, recent discoveries of new TFLs in Paraguay [*Houben et al.*, 2014], Australia [*Werner and Laattoe*, 2016] and Zambia [*Chongo et al.*, 2015] indicate that TFLs may be more widespread than previously thought. No previous attempt to review their occurrence, origins and controlling factors has been made.

[Insert Figure 1 here]

Figure 1. Global overview of brackish or saline (>1000 mg/L) groundwater occurrence at intermediate depths (< 500 m below ground level). Original source [*Van Weert et al.*, 2009].

This study combines the known mechanisms that form TFLs into a typology, based on a review of previous TFL studies. We define a TFL as a buoyant low-salinity groundwater lens that persists between recharge events and is disconnected from the hydraulic and chemical influences of modern seawater. Here, buoyancy arising from the density contrast is considered the primary mechanism that prevents mixing between saline groundwater and lower salinity TFL water, where both water types occur within a single host aquifer. The characteristics of TFLs are perturbed in time by recharge mechanisms, groundwater-surface water interaction, atmospheric changes and biogeochemical reactions. Our TFL definition excludes low-salinity groundwater deposits where geology prevents mixing with in-situ saline groundwater. Additionally, TFLs resulting from paleo processes are not considered, primarily because no such features have been encountered in previous studies. A global perspective and inventory of known TFLs and their characteristics is presented as the first attempt to categorize these previously under-recognized but critical features of global hydrogeological systems. An increased understanding of processes that form TFLs will contribute to their future management and will raise awareness of the threats to TFL stability and persistence.

2. Known terrestrial freshwater lenses

A review of the currently available literature identified twenty publications describing the locations of fifteen TFLs. Six studies focus on a specific TFL, providing a well-documented account of the hydrogeology and relevant factors that control the lens location and formation. In these cases, a combination of geophysical surveys, geochemical analyses and/or numerical modelling is used to characterize the TFL. The remaining thirteen publications identify TFLs, but offer limited information regarding their characteristics. In two cases, TFLs supported decades of freshwater exploitation by local communities [*Bauer et al.*, 2006; *Houben et al.*, 2014] prior to the published study.

A categorization scheme for the known TFLs is illustrated schematically in Figure 2. Six TFL types have more than one occurrence globally; another two TFL types are represented by single incidences. The first TFL type involves ephemeral surface water bodies in semi-arid and arid settings where the lens occurs beneath a normally dry streambed (Figure 2a). The lens persists through the dry season and is recharged by infiltrating stream water in the wet season. Examples of this type of lens include the Nxotega and Shashe River valleys in Botswana [*Linn et al.*, 2003; *Bauer et al.*, 2006] and Cooper Creek in Queensland, Australia [*Cendón et al.*, 2010]. In the Shashe River Valley, the local population exploits the TFL that is recharged by a losing ephemeral stream fed by floodwaters from the Okavango inland delta [*Bauer et al.*, 2006]. However, this water use appears to be degrading the lens, as increasing salinities are observed in extraction wells. Flows in Cooper Creek recharge multiple TFLs, which return freshwater to the creek during dry seasons, allowing shallow ponds to persist when streamflow ceases [*Cendón et al.*, 2010]. Channel scour during high flow events in Cooper Creek plays a key role in infiltration by providing enhanced connectivity between the river and the TFL. Steep regional hydraulic head gradients in the area produce asymmetric lenses that spread downstream from the recharge locations.

[Insert Figure 2 here]

Figure 2. Conceptual models of known TFL types and their global distribution. Diagrams depict TFL formation associated with: (a) ephemeral surface water bodies, (b) continuously losing perennial surface water bodies, (c) continuously gaining perennial surface water bodies, (d) topographic mounding, (e) focused rainfall recharge, and (f) anthropogenic effects. Question marks identify reported TFLs with uncommon characteristics.

The second TFL type is associated with a continuously losing perennial surface water body (Figure 2b) that discharges freshwater to the surrounding aquifer, which otherwise contains saline groundwater. The conceptual diagram for this TFL type consists of a lens connected to a losing river or lake, whereby the lens size changes in accordance with variations in the hydraulic gradient between the groundwater and surface water. The TFL extent is controlled in part by the rate of recharge from the losing surface water body [*Cartwright et al.*, 2010] and a combination of aquifer and water parameters. The lens expands when surface water levels are high due to steepening of the hydraulic gradient in the riparian zone that causes the infiltration of floodwaters. Lens contraction occurs during dryer periods as the surface water levels fall and the hydraulic gradients and/or reverse. Australia's Murray River and the Zambezi River in Zambia produce lenses of this type [*Cartwright et al.*, 2010, 2011; *Chongo et al.*, 2015]. The Murray River TFL, located in the Colignan-Nyah region of Victoria, was characterized primarily from geochemical analyses [*Cartwright et al.*, 2010], whereas "low resistivity anomalies" in a geophysical survey lead to the discovery of the TFL on the Zambezi River [*Chongo et al.*, 2015]. Both rivers traverse semi-arid regions where the salinity of the groundwater beneath the losing river approaches, and locally exceeds, that of seawater. The geochemistry of the Colignan-Nyah TFL revealed a lack of vertical recharge from flood inundation, which was attributed to extensive surficial clay deposits on the floodplain. Consequently, the primary recharge pathway for the Colignan-Nyah TFL is through the base and banks of the river during high river-stage events.

Aquifers connected to continuously gaining, perennial surface water bodies host the third type of TFL (Figure 2c). Here, surface water levels are predominantly below those of the surrounding saline aquifer. Consequently, the hydraulic gradient drives denser saline groundwater into the less dense fresh surface water. Buoyancy that results from the density difference between the fresh surface water and saline groundwater permit a TFL to float above the saline groundwater, despite both density and hydraulic forces acting to oppose it. This TFL type was recently postulated mathematically and is thought to apply to gaining reaches of the Lower River Murray in South Australia [*Werner and Laattoe*, 2016]. Airborne electromagnetic surveys [*Viezzoli et al.*, 2009] and laboratory experimentation [*Werner et al.*, 2016] provide evidence for the plausibility of this unlikely form of TFL. Further research is required to characterize this type of TFL, to assess its recharge and discharge mechanisms and the lens hydrodynamics.

The fourth TFL type is an oceanic island analogue (Figure 2d), whereby topographic highs lead to mounding of freshwater in relatively flat regions that otherwise contain shallow saline groundwater. Evaporative discharge of groundwater in the lowlands maintains a body of saline groundwater similar to the sea surrounding an island. Enhanced net recharge occurs in topographic highs because the thick unsaturated zone impedes the evapotranspiration of groundwater from the deeper water table. Greater permeability in the elevated recharge area facilitates increased infiltration rates and allows for the formation of freshwater lenses. At Benjamín Aceval, Paraguay, local inhabitants exploit a TFL of this type located beneath sandstone hills in an otherwise flat lowland area with groundwater salinity close to that of seawater [*Houben et al.*, 2014]. Threat of salinization and contamination of the lens from sewage prompted a comprehensive investigation of the TFL. Geochemical data obtained during an investigation of dune migration patterns in White Sands (New Mexico, USA) revealed a similar TFL located beneath a topographic high [*Langford et al.*, 2009]. The lens has a stabilizing effect on the dune by supporting the growth of vegetation.

The fifth TFL type is created by focused recharge from rainfall runoff (Figure 2e), which occurs in landscapes dominated by relatively impermeable surface geology with topography that channels runoff to depressions. Increased vertical permeability in depressions due to fractures, karst conduits or weathering facilitates rapid infiltration to an otherwise saline aquifer. TFLs of this type are reported in the desert regions of Kuwait [*Al-Sulaimi et al.*, 1996; *Kwarteng et al.*, 2000; *Al-Senafy and Abraham*, 2004; *Milewski et al.*, 2014] and Oman [*Young et al.*, 2004], where the annual rainfall rarely exceeds 200 mm/yr. Precipitation occurs here as infrequent storms exceeding 20 mm/day that produce significant runoff over the relatively impermeable terrain, causing localized recharge from topographic depressions [*Kwarteng et al.*, 2000]. A similar process forms TFLs on the Eyre Peninsula (South Australia) [*Kleinig*, 2012] in areas where the average rainfall ranges from 250 to 450 mm/yr. Here, sinkholes in calcrete and other carbonate formations provide a mechanism for localised recharge of rainfall runoff in regions otherwise dominated by saline groundwater. At Stockyard Plain, in South Australia, geophysical surveys revealed another TFL of this type beneath a surface depression [*Barrett et al.*, 2002]. The 240 mm/yr annual average precipitation in this region is sufficient to maintain a TFL beneath karst sediments.

TFLs resulting from anthropogenic effects (Figure 2f) represent the sixth TFL type. For example, shallow but laterally extensive TFLs have developed over paleo-marine groundwater in the interfluve regions of the Indus Plain in Pakistan [*Asghar et al.*, 2002]. Here, the average rainfall is approximately 230 mm/yr, and the lenses are the result of freshwater infiltration from intensive flood irrigation to the otherwise saline aquifer. Recharge to the TFL is further enhanced by infiltration from Monsoon rains and overbank flooding. In this example, the TFL has both natural and anthropogenic sources of freshwater, but its persistence is dependent on the irrigation infiltration. Famers exploit the 30 to 150 m thick TFL for irrigation using skimming wells. Further examples of anthropogenic TFLs are reported in studies of the saline floodplains of the River Murray in Australia [*Berens et al.*, 2009; *Alaghmand et al.*, 2014, 2015]. Here, losing river conditions are induced by pumping, with the intention of creating a TFL from which trees can access freshwater, thereby enriching the environmental assets within the floodplain. Freshwater lenses of drained polders in the Netherlands are arguably the most investigated anthropogenic TFLs [*Schot et al.*, 2004; *Eeman et al.*, 2012; *de Louw et al.*, 2013]. These lenses are created by drainage systems that control the saltwater head to levels that inhibit salinization of adjacent irrigated cropped land [*de Louw et al.*, 2013]. Whether these are strictly TFLs rather than coastal/marine-based lenses is arguable. Many conceptual models are possible for anthropogenic TFLs but for brevity, we adopt the Indus Basin example in illustrating this TFL type in Figure 2f.

There are other single-incident types of TFLs that demonstrate characteristics that differ to the examples given in Figure 2. For example, a TFL is located above the brackish groundwater of a confined saline aquifer in Geneva (Florida, USA) [*Panday et al.*, 1993]. This TFL is recharged by the fresh groundwater in the overlying surficial aquifer through a region of increased vertical permeability in the confining unit that separates the two aquifers [*Panday et al.*, 1993]. This is markedly different from all other reported TFL cases where the lens exists in the phreatic aquifer and receives recharge via surface sources. In the Kerang Lakes region of northern Victoria, Australia, researchers identified a TFL with no apparent recharge mechanism, which currently exists as a relic of a recently altered hydrologic regime [*Chambers et al.*, 1996]. A large freshwater body, believed to be the paleo Okavango Megafan, was identified beneath the world's largest salt pan complex (the Makgadikgadi Basin, Botswana) through remote sensing methods

[*Podgorski et al.*, 2013]. Clay-rich lacustrine deposits prevent the freshwater from mixing with overlying saltwater, and therefore this freshwater body does not comply with the current definition of a TFL.

A tabulated summary (Table 1) of the causal factors for known TFL types reveals two broad categories, namely, lenses formed by freshwater inputs from surface water bodies and from other sources (e.g. rainfall, anthropogenic sources, leakage through aquitards). Both topography and geology are key factors in the formation of TFLs that are unrelated to surface water features. The host aquifer geology is shown to influence both the TFL and the regional saline groundwater [*Bauer et al.*, 2006]. The significance of flood inundation recharge for both continuously losing and continuously gaining river lenses is unresolved in some situations [*Chongo et al.*, 2015; *Werner and Laattoe*, 2016], and requires further investigation. Further information about each identified TFL is provided in a table as supplementary material with the electronic version of this document.

Table 1. Summary of causal factors identified for each TFL type, where **P** indicates primary and **S** indicates secondary causal factors.

			TFL type					
			1	**2**	**3**	**4**	**5**	**6**
			Ephemeral surface water	Continuously losing perennial surface water	Continuously gaining perennial surface water	Topographic mounding	Focused rainfall runoff	Anthropogenic
Sources of fresh water	Diffuse rainfall recharge		**S**	**S**	**S**	**P**		**S**
	Rainfall runoff						**P**	
	Flooding			**S**	**S**			**S**
	Pumping							**P**
	Irrigation							**P**
	Surface water bodies	Losing perennial		**P**				
		Losing ephemeral	**P**					
		Gaining perennial			**P**			
Physiographic factors	Topography					**P**	**P**	**S**
	Geology		**S**	**S**	**S**	**P**	**P**	**S**
	GW/SW interaction		**P**	**P**	**P**			**S**

3. Functional significance of known TFLs

Table 2 lists the reported significance of the TFLs encountered in the current review. TFLs in Botswana, Paraguay, Pakistan, and Florida are exploited for irrigation and drinking water [*Asghar et al.*, 2002; *Bauer et al.*, 2006; *Houben et al.*, 2014]. In Cooper Creek, Australia, the TFLs provide the only source of dry-season fresh water for local flora and fauna [*Cendón et al.*, 2010]. The TFL in White Sands, New Mexico also supports vegetation growth in an otherwise highly-saline environment [*Langford et al.*, 2009]. The shallow TFLs in the Okavango Delta region support phreatophytes, which differ to surrounding vegetation overlying saline groundwater [*Bauer-Gottwein et al.*, 2008]. Similarly, River Murray ecologists consider the occurrence of low-salinity groundwater within TFLs intrinsic to the health of the floodplain vegetation [*Jolly et al.*, 1993; *Doody and Overton*, 2008]. In addition, these TFLs prevent increased salt loads to the River Murray in periods of low flow, when the hydraulic gradient between the river and surrounding floodplains reverses, causing sections of the river to transition from losing to gaining [*Alaghmand et al.*, 2015]. In Kuwait, the TFLs represent the only natural source of freshwater in the country [*Kwarteng et al.*, 2000], and are used extensively for drinking water supply [*Milewski et al.*, 2014].

Table 2. Significance of TFLs identified in the current study

Location	TFL Significance
Murray River, Australia	Critical for floodplain vegetation and reduces salt flux to the river during drought periods
Shashe River Valley, Botswana	Primary source of freshwater for local populace
Cooper Creek, Australia	Only source of dry-season freshwater for ecosystems
Benjamin Aceval, Paraguay	Primary source of freshwater for local populace
White Sands, New Mexico, USA	Enhances vegetation to stabilise dunes
Geneva, Florida, USA	Source of freshwater for household use and irrigation
Kuwait	Only natural supply of fresh drinking water
Indus Plain, Pakistan	Used for irrigation

4. Concluding remarks

TFLs represent arguably the most understudied hydrogeological systems on Earth. This is despite the fact that they generally comprise high-value freshwater resources in rainfall-limited settings, where their functional significance is commonly a multi-faceted combination of human and ecological uses. Similar to surface oases, TFLs can provide a source of fresh water in regions that are otherwise uninhabitable [*Bauer et al.*, 2006; *Cendón et al.*, 2010]. However, in contrast to conventional oases [*Fitzsimmons*, 2005], the presence of a TFL is often significantly less apparent [*Kwarteng et al.*, 2000; *Chongo et al.*, 2015] to the extent that some occur in locations that defy hydrogeological intuition [*Chambers et al.*, 1996; *Werner and Laattoe*, 2016].

TFLs form from a wider range of processes than their frequently studied coastal counterparts, and consequently, TFLs are more likely to involve hydrodynamic behaviour that has not previously been considered. For example, TFLs differ to coastal lenses in the terrestrial occurrence of steep saline groundwater gradients [*Cendón et al.*, 2010], episodic or focused recharge from various sources such as flooding and river flow [*Kwarteng et al.*, 2000; *Young et al.*, 2004; *Bauer et al.*, 2006; *Cendón et al.*, 2010; *Milewski et al.*, 2014], and the interplay between riverine conditions and TFLs [*Cartwright et al.*, 2010; *Werner and Laattoe*, 2016]. The dynamic behaviour of TFLs coupled with potential changes in the salinity distribution of the host aquifer is challenging to quantify and model [*Bauer et al.*, 2006]. Phytotoxicity of salinity and salt accumulation by plant transpiration are key ecohydrological feedback mechanisms in near-surface TFLs that need to be better understood and characterized for successful quantitative analysis of TFL behaviour [*Bauer et al.*, 2006; *Bauer-Gottwein et al.*, 2008]. Moreover, the global prevalence of saline groundwater in the shallow subsurface increases the possibility for undiscovered TFL types, and therefore, it is likely that the typology presented herein is incomplete.

Opportunistic discoveries [*Barrett et al.*, 2002; *Chongo et al.*, 2015] and first-documented cases of long-exploited TFLs [*Bauer et al.*, 2006; *Houben et al.*, 2014] imply that TFLs are potentially more common than the limited number of known occurrences suggests. With recent interest in potential exploitation of TFLs for both human use [*Cartwright et al.*, 2011; *Milewski et al.*, 2014] and ecological benefit [*Berens et al.*, 2009; *Alaghmand et al.*, 2015], combined with their often fragile conditions, there is clear impetus for further TFL investigation. However, further research is needed to evaluate if conventional approaches to freshwater lens investigations apply to TFLs, given the disparity in formation between TFLs and coastal lenses. Increased use and advances in geophysical survey techniques [*Viezzoli et al.*, 2009; *Chongo et al.*, 2015] will likely contribute to future TFL discoveries. Additionally, those comprehensively studied TFLs clearly indicate that strong characterisation is required for successful TFL management [*Bauer et al.*, 2006; *Houben et al.*, 2014]. Finally, we conclude that TFLs are arguably the most vulnerable freshwater resources on earth, given the paucity of TFL information, the varied and/or episodic nature of TFL recharge, and the critical services provided by TFLs in otherwise water-limited settings, amongst other factors.

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