

Modelling the connections between internally and externally drained basins using GIS, Google Earth[®], and remote sensing

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Abstract

The development of internal drainage is intimately tied to the tectonic and climatic history of an area, but research into the exact causes and processes of internal drainage is constrained by the ability to accurately delineate both internally and externally draining watersheds. Until recently, existing global catalogs of internally drained regions were either hand-drawn or based upon digital elevation models whose resolution is much lower than those currently available. Here, the World Wildlife Fund's HydroBASINS dataset is analyzed in a GIS program to identify points of former connectivity between endorheic and exorheic basins, to identify possible palaeolakes and palaeo-distributary channels, and to quantify on a global basis the extent of area lost to internal drainage for 101 large watersheds. The results have been made available in Google Earth[®] KMZ files, and a sample workflow is presented which uses the data to approximate the relative importance of tectonic vs climatic factors in initiating endorheism. As an example of how the dataset and workflow can be used, the drainage history is modelled for endorheic watersheds within two very different tectonic regimes, the Afar region of northeastern Africa and the Northern Territory of Australia. The methodology is readily adaptable to other endorheic basins and offers the ability to create drainage history models which can help in research areas such as climate change investigations and groundwater and economic mineral prospecting.

Keywords

Endorheic basins, HydroBASINS, internal drainage

I Background and introduction

Internally drained regions are networks of hydrologic basins that have lost their connection to oceanic base level through aridification, glaciation, tectonic uplift, modification of the drainage network by volcanism, or by some combination of the above. (Allen, et al., 2013; Cretaux, et al., 2013; Fornari, et al., 2001; Garcia-Castellanos, 2006; Hammer, 1986; Nicoll, 2010; Sobel, et al., 2003; Walker, et al., 2011). Often associated with periods of climatic change, the onset of internal drainage may have a significant impact upon many geologic processes. For example, the inability of fluvial systems to remove mass from uplifting basins may store gravitational potential energy in the crust, favoring the migration of deformation to lower-elevation areas (Garcia-

Castellanos, 2007; Sobel, et al., 2003). The onset of internal drainage can also shift the erosivity of a river from transport-limited to supply-limited, due to the loss of contributing drainage area and erosive ability (Attal, et al., 2008), and sediment discharge to the ocean may be controlled by the loss or gain of drainage to the main river course (Clift and Blusztajn, 2005). The arid and semi-arid lakes found in many endorheic basins may serve as sensitive indicators of emerging climatic changes (Kotwicki and Allan, 1998), and the reduction in water resources due to the onset of internal drainage can also contribute to the decline of major civilizations (Gasse, 2000; Rajawat, et al., 2003; Roy and Jakhar, 2001; Sankaran, 1999; Wanner, et al., 2008). Consequently, knowledge of the extent of internally drained regions should be an important factor when considering the geologic history of a region.

Early attempts to measure the amount of internal drainage were constrained by the limits of both existing cartographic technology and available hydrologic and geomorphologic data. The first cartographic representation of the global extent of interior drainage was made by Heinrich Berghaus, a German surveyor and student of Alexander von Humboldt, whose *Physikalischer Atlas* was the first to bring together in map form the accumulated knowledge at that time of both the social and physical sciences (Berghaus, 1892; De Martonne, 1927; Landmark thematic atlases, 2012) (Fig. 1). According to De Martonne (1927), Murray (1886, 1887) used a planimeter on Berghaus' map to estimate that 11,486,350 square miles (29,749,510 sq km) of the Earth's land surface, was internally drained. Penck (1894), also working off of Berghaus' map, estimated 29,900,000 sq km for the extent of internal drainage.

De Martonne (1927) was the first to use the terms “endorheic” and “exorheic” to distinguish the two separate domains of interior and oceanic drainages, deriving them from the Greek word for “flow,” as well as the term “arheic” to distinguish areas of exorheic drainage which did not receive enough rainfall to maintain perennial streams. He estimated that the amount of endorheic and arheic drainage on the Earth's surface totaled 41,838,000 sq km, of which 27,991,000 sq km were arheic, leaving 13,847,000 of the Earth's surface in the true endorheic domain.

The introduction of digital elevation models (DEMs) in the latter part of the 20th century allowed for more refined estimates of the global extent of internal drainage. Vörösmarty, et al. (2000) introduced STN-

30p, a hydrologic model developed at or close to 30 minute (latitude-longitude) spatial resolution. Using STN-30p, they calculated that 13% (17.4×10^6 km²) of the non-glaciated surface of the Earth is endorheic, a figure later cited by Meybeck, et al. (2001) in a study of global relief distribution.

Döll and Lehner (2002) introduced a global 30-min drainage direction map which identified 663 out of 3934 drainage basins as draining to inland sinks, but did not provide area measurements for the basins. Garcia-Castellanos, et al. (2003) used a figure of 20% when stating that endorheic basins collect only 2% of global river runoff. Shiklomanov, et al. (2003) estimated that 30.1 million sq km and 20% of the total land area of Earth is endorheic.

A major advance in the development of digital global hydrologic models was the introduction of the World Wildlife Fund's HydroSHEDS project, which resampled the near-global 90m elevation data of the Shuttle Radar Tomography Mission (SRTM) to a DEM resolution of 500m and created a global hydrologic database that could be manipulated in a Geographic Information System (GIS) (Lehner, et al., 2006, 2008a). HydroSHEDS offered true digital coverage of watersheds on a global scale, but the dataset did not distinguish endorheic from exorheic areas.

In 2013, Lehner and Grill (2013) introduced HydroBASINS, a high resolution global dataset of hydrologic shapefiles derived from the HydroSHEDS dataset which allows both watershed boundaries and sub-basin delineations to be analyzed at a global scale. HydroBASINS is a series of hierarchical sub-basins that follows the topological concept of the Pfafstetter coding system (for a complete description of the methodology used, see Lehner & Grill (2013)). Twelve individual polygon layers of increasingly finer scales of watershed delineation were created by applying the concept of nested basins derived from the underlying flow direction grids of the HydroSHEDS data, from continental-scale Level 1 basins at the coarsest resolution to the smallest Level 12 basins with the finest resolution. Another layer, Level 00, combines the Level 12 basins with GIS database attributes so that all the levels can be combined and dissolved, allowing many levels of geospatial analysis (Fig. 1). HydroBASINS includes endorheism as an attribute, which makes it possible to calculate the percentage of endorheic area for the Earth's surface at an areal resolution of 500m (Table 1).

(Fig. 1)

Table 1. Percentage of exorheic and endorheic area by continent.

Here, the GIS program Global Mapper is combined with the HydroBASINS dataset to estimate the palaeodrainage from endorheic regions into the world oceans. This was achieved by using Global Mapper's watershed generation process to virtually fill every endorheic basin in the HydroBASINS dataset and trace the resulting stream network to the sea. The resulting streamflows connected every endorheic basin with an exorheic watershed, enabling estimation of the percentage of formerly exorheic regions lost to the watersheds of the world's largest river basins. The process also enabled identification of the locations of possible palaeolakes, along with possible palaeo-deltaic distributaries at watershed mouths. The resulting geospatial and quantitative data were used to identify connections between exorheic and endorheic basins and the locations of possible palaeolakes and palaeo-deltaic distributaries, and to estimate the percentage of formerly exorheic regions lost to the watersheds of the world's largest river basins.

II Methodology

Global Mapper's watershed generation process was used with a 2-km grid spacing ETOPO1 DEM (Amante and Eakins, 2009) to create streamflow to the ocean from points generated at the minimum elevation of every endorheic basin in the HydroBASINS dataset. Since the purpose of the watershed generation process was not to recreate existing stream drainage but to determine the final marine outlet for every polygon, the streamlines created in this analysis are not to be thought of as actual streams, although they eventually do merge into real channels, but rather as theoretically possible flowpaths between an area polygon and an endpoint in the ocean. The streamlines were then superimposed in Global Mapper upon all HydroBASINS exorheic basins larger than 25,000 sq km, which account for about 60% of the world's non-glaciated land surface. Fifty-eight percent of the endorheic basins, accounting for 70% of the Earth's endorheic area, had streamlines which reached the ocean through the large exorheic basins. The endorheic basins and the exorheic basins through which their streamflows reached the ocean were then grouped into DEM-derived networks (DDNs), labeled by the name of the largest river in the exorheic basin. If there was no large through-going stream within an exorheic basin, the

DDN was labeled with either the name of a coastal feature or a smaller stream within the watershed (see Fig.2 (a-e) for examples).

(Fig. 2)

The Global Mapper files were then converted into Google Earth[®] KMZ files for each of the five continental land masses. Geospatial features within the KMZ files included the following:

Polygons:

- (a) Every endorheic basin in the HydroBASINS dataset;
- (b) Every exorheic HydroBASIN basin > 25,000 sq km through which endorheic streamflow lines reached the ocean;
- (c) Closed contour areas marking endorheic area depressions and potential palaeolakes.

Lines:

- (a) Streamlines from the lowest elevation point of every endorheic basin, classified by whether or not they drained into an exorheic basin >25,000 sq km;
- (b) Streamlines extracted from the HydroSHEDS 30-second river network shapefile, which represent the actual drainage lines of all the exorheic basins > 25,000 sq km.

Points:

- (a) The lowest elevation point in every endorheic basin from which streamflow was initiated in Global Mapper's Generate Watershed process;
- (b) Every intersection between endorheic streamflow lines and the boundary of the exorheic basin within a DDN, for investigation as possible wind gaps between exorheic and endorheic basin;.
- (c) The outlet to the ocean of a DDN, when the location of that outlet varied significantly more than 4 km from the outlet of the HydroSHEDS river network, for investigation as possible palaeo-distributary channels.

All the lines, points and polygons in the study were assigned unique index numbers and exported by continent into Google Earth[©] KMZ files¹.

1 *Areas of uncertainty in the analysis*

In any GIS watershed generation process, major parameters affecting final stream network quality include the choice of the underpinning DEM and the algorithms used to fill sinks and create flow direction.

a *DEM.* While watershed generation is a standard GIS processes, the quality of the produced stream network will be directly influenced by the characteristics of the underpinning DEM. The ETOPO1 DEM used in the analysis was compiled from fifteen global, bedrock, coastal and regional bathymetric datasets, and local variations in resolution of the underlying datasets may be reflected in the ultimate location of the endpoints used to aggregate streamflow generated on the continents.

b *Sink filling.* All hydrologic modeling relies on some form of overland flow simulation to define drainage networks, of which the first step is identifying and removing depressions (Garbrecht and Martz, 2000; Zandbergen, 2006). Most DEMs contain depressions, defined as areas without an outlet, which can either be real or artificial (Zandbergen, 2006; Wu et al., 2008). The two main techniques for removing depressions are either filling or breaching (Wilson, 2012). Breaching a depression lowers the elevations of the cells in a DEM along a breach channel, resulting in cell elevation values either the same or lower than the original DEM. Filling effectively floods the depression until it overflows, resulting in cell elevation values that are the same or higher than the original DEM, and has become the most widely used method, in part because of its relative simplicity.

Global Mapper removes depressions with a sink-filling method based upon that of Planchon and Darboux (2002). Instead of gradually filling depressions from the bottom up, Global Mapper first inundates the DEM surface with a virtual layer of water and then removes the excess water. Depressions are replaced with a slightly sloping surface which is then used for drainage network extraction. Because the purpose of the study was to fill every endorheic basin in the world, the largest value possible for sink filling was used (5000m).

¹ High resolution PDF images of endorheic streamlines available in supplementary files. Google Earth KMZ files available online at _____

c ***Flow direction algorithm.*** Once the depressions are filled in Global Mapper's watershed generation process, flow directions are determined with a D-8 algorithm, which identifies the steepest downslope flow path between each cell of a raster DEM and its eight neighbors, and defines this path as the only flow path leaving the raster cell (O'Callaghan and Mark, 1984; Wilson et al., 2008). The nearest neighbor method, which samples the original value of the nearest pixel, was used for the watershed generation process. This approach maintains elevation values without any additional smoothing effects, and has been the technique of choice in other studies using resampling to produce coarser DEMs for the purpose of determining the effects of DEM resolution (Zandbergen, 2006). For fine resolution DEMs with many grid points, it is common to aggregate points before flow computation (Le Coz et al., 2009), but since the ETOPO1 DEM was already at a relatively coarse level of resolution, no resampling was done during the watershed generation process.

d ***Uncertainty analysis.*** To test the robustness of the DEM-derived stream networks, the watershed generation process was repeated for all the endorheic basin minimum elevation points using bicubic and bilinear interpolation methods, which produce flowpaths differently than the nearest neighbor method. Additionally, to account for the possible influence of the location of the initial point upon the generated streamflow, four randomly located points were created within each endorheic basin, and the streamflow generation process repeated for the resulting set of points, using the nearest neighbor, bicubic and bilinear interpolation methods. In total, 177,245 additional streamflows were produced and analyzed to determine their exit into the ocean.

Each endorheic basin was then classified as to whether all the uncertainty analysis streamflows generated from that basin reached the ocean at the same general location as the initial streamflow generated from the basin minimum elevation using the nearest neighbor method, or whether one or more of the flowpaths reached the ocean in a different location than the nearest neighbor/endorheic minimum flowpath.

Overall, the uncertainty analysis created different oceanic endpoints for only 3% of the total number of endorheic basins, accounting for 3% of the total global endorheic area. The small percentage of endpoint deviation supports the reliability of the DDN-creation process for large-scale global analysis.

III Results

The process generated 101 DDNs with a total area of about 66,800,000 sq km, accounting for about 50% of the Earth's non-glaciated land surface².

1 Identification of exorheic-endorheic basin connections

The intersections of endorheic streamflow lines with the major exorheic basin of the DDN were identified as possible wind gaps representing the last point of connectivity to the neighboring basin prior to the onset of internal drainage (Lee, 2015).

One test of the predictive capability of this assumption would be to compare these hypothetical wind gaps with known wind gaps. For example, the point generated for the outlet of endorheic DDN streamflow from Palaeolake Bonneville in Idaho, US, coincides with the location of Red Rock Pass, which has been identified as the most recent drainage outlet for the lake (Gilbert, 1890; Nishizawa, et al., 2013; O'Connor and Beebee, 2009; O'Connor and Costa, 2004) (Fig. 3). This suggests that other such points identified in the study may represent points of past connectivity between endorheic and exorheic basins.

(Fig. 3)

Another test would be to determine whether the lowest point on the boundary of an endorheic basin coincided with the exit of streamflow from the basin, since the lowest elevation along the basin boundary should represent the spillover point for drainage from a closed basin prior to the loss of connectivity with surrounding watersheds (Lee, 2015). To test this hypothesis, points were generated at the minimum elevation on the boundary of every endorheic basin, and Global Mapper was used to determine whether the DDN streamflow intersected the basin boundaries at the boundary minimum elevation point. To allow for the 2 km spacing of elevation points in ETOPO1, any streamline and basin boundary minimum elevation point within 5 km of each other were considered to be coincident.

Under this criteria, about 94% percent of basin boundary minimum elevation points were coincident with at least one streamline, and should therefore represent true wind gaps marking the spillover point of the basin prior to the onset of interior drainage. A little over a third of the points not coincident with streamflow

² Detailed table of DDN area percent distribution available in supplementary files.

were located within a topographic depression indicated by a closed contour area, or were shared between two basins while the DDN streamflow intersection (hypothetical wind gap) lay elsewhere. The basins on whose boundaries these points lie are interpreted to have originally belonged to a larger palaeolake which split into smaller subbasins upon the onset of internal drainage, and which continued to maintain hydrologic connections until separated by a topographic sill (for example, see Fig. 3).

Of the remaining points not coincident with streamflow, most were located less than 15 km from a streamline. A few were located in basins with multiple low points on the basin boundary that were similar in depth, for example, basins in dune fields. Given the relatively coarse 2 km spacing of elevation points on the ETOPO1 DEM, this resulted in a margin of error which caused GM to calculate a border minimum elevation in a different location than where the streamflow exited the basin.

This analysis demonstrates the utility of the DDN streamflow for identifying wind gaps marking former spillover points of endorheic basins.

2 Identification of palaeolakes

Depressions marked by closed contour lines in this analysis suggest the locations of ancient palaeolake shorelines, many of which may not be detected by conventional stratigraphic and mapping methods because of obscured or eroded shorelines. As support for this assumption, there is a strong agreement between the results of the analysis and the currently accepted extents of large palaeolakes identified by other researchers, including Palaeolakes Bonneville in Utah, US (Fig. 3) (Nishizawa, et al., 2013), Chad in Africa (Leblanc, et al., 2006) and Darfur, in Sudan, Africa (Elmahdy, 2012; Ghoneim and El-Baz, 2007).

3 Identification of palaeo-deltaic distributaries

A primary use of GIS watershed processes is to recreate existing stream networks for hydrologic modeling (Le Coz, et al., 2009; Lehner, et al., 2008b). With a perfect correlation of DEM elevation points to actual topography, there should be a one-to-one correlation of DEM-derived networks with actual basins. The limitations of existing elevation grids and computer processing technology, however, often result in GIS-derived stream networks that differ from actual stream networks, requiring post- or pre-processing modification of either the underpinning DEM or the derived stream networks (Callow, et al., 2007; Craddock, et al., 2010;

Lehner and Grill, 2013; Lehner, et al., 2006, 2008b). Caution should therefore be applied in evaluating GIS-derived palaeodrainage maps.

The stream networks created through Global Mapper's watershed generation process mimicked existing rivers most closely in areas of high relief, and exhibited the greatest variations from actual stream networks in flat areas, where vertical resolution is below the threshold needed to accurately model flow (Callow, et al., 2007; Zhao, et al., 2009). For the purposes of this study, however, the lack of a correspondence between the endorheic streamflow lines and actual streams may reveal information about former streamflow patterns. For example, lower resolution DEMs tend to reduce slopes and to decrease flow-path lengths because of meander short-circuiting (Wolock and McCabe, 2000; Wu, et al., 2008). This smoothing out of topography leads to the "healing" of narrow gorges and more recent stream channels whose width is narrower than the spacing of DEM elevation points, and is most obvious in flat areas such as deltas and floodplains (Lehner, et al., 2008b; Sørensen and Seibert, 2007). Streamlines generated on these smoothed surfaces will tend to follow larger-scale gradients, often resulting in deviations from actual stream flow. If the geomorphological signature of a current drainage channel is smaller than the spacing of the elevation grids, then generated streamflows may reflect former, larger wavelength palaeodrainages (Le Coz, et al., 2009). If so, these discrepancies move from the category of computer error into that of data.

The Mississippi River is a good example. Figure 4 shows the pattern of the DDN streamflow lines superimposed upon a contour map derived from a 500m CGIAR DEM (Jarvis, et al., 2008). Within the Mississippi River delta, the DDN streamflow lines depart the actual river channel in central Louisiana and flow through the Atchafalaya River basin.

(Fig. 4)

The Atchafalaya basin is the youngest of several intertributary basins formed by avulsion of the major tributary of the Mississippi River (Gosselink and Pendleton, 1984). It receives one third of the flow of the combined Mississippi and Red Rivers, and is actively prograding into Atchafalaya Bay (Barras, et al., 2008). During the twentieth century, manmade modification of the Mississippi River channel near Old River, Louisiana, resulted in more and more flow diverting down the Atchafalaya River, requiring construction of the

Old River Control Structure in order to prevent the Mississippi River from completely switching its channel (Mossa, 1996; Turnipseed, et al., 2014; U.S. Army Corps of Engineers, 2009). The flow directions of the DEM-derived streamlines, therefore, clearly reflect the influence of an actual palaeochannel of the Mississippi River which would be the preferred channel of the river apart from manmade intervention.

Similar topographic analyses on other DDNs whose streamflows diverge from the actual outlet to the ocean may reveal other significant geomorphic factors manifested in the shifting of DEM-derived streamflow away from the actual channel of the river basin in which they are located. In this study, 49 DDN oceanic outlets were identified that deviated significantly more than 4 km from the oceanic outlet of the actual river network as represented by the HydroSHEDS 30-second river network (variations of 4 km or less would fall within a reasonable margin of error of accuracy, since the grid cell spacing of the ETOPO DEM is 2 km).

4 Quantification of watershed area lost to internal drainage

If it can be assumed that all endorheic and exorheic basins connected by a DDN were once part of the same watershed, the proportion of endorheic area to the total area of the DDN can give an approximation of the percentage of land lost to a watershed from the onset of internal drainage. This assumption is justifiable if the lowest points on the boundaries of internally drained basins can be shown to represent former connections to contiguous externally drained basins. While this may not be true for very small basins such as karstic or volcanic crater lakes, this general assumption seems justified based upon the preceding wind gap analysis. Additionally, it seems improbable that large scale basins could exist throughout geologic time without ever being connected to the ocean, especially since most areas of internal drainage once received much more precipitation in the past (e.g. north Africa, central Australia, North American Basin and Range region, etc.) (Harvey, 1999; Joussame et al., 1999; Martin, 2006).

If correct, the analysis shows that twelve of the world's exorheic river basins greater than 25,000 sq km were more than 50% larger in the past (Table 2). Seven of these may have shrunk by as much as two-thirds due to the onset of endorheic drainage, and the Uzboy River appears to have lost 99% of its original watershed area (Fig. 2e). It should be noted, however, that the total ratio of endorheic to exorheic area within a DDN may vary over time, due to the activation and de-activation of connections between basins. A DDN can be more properly

thought of as a cascade of potential hydrologic connections between basins at the head of a DDN and basins at the ocean, which are activated and de-activated over time due to factors such as sea level rise, climatic events and tectonic movements. Additionally, the same factors may cause the basins at the DDN borders to lose or gain drainage area, thus affecting the overall size and shape of the DDN itself.

Table 2. DDNs with 50% or more endorheic area, indicating they may have lost over half their original watershed to internal drainage.

IV Application of DDNs for palaeolake analysis

Analyses of DDNs can be particularly useful for studying remote areas where harsh environmental conditions and/or political stability make fieldwork difficult and expensive. In the following case studies, two DDN analyses are combined with Google Earth[®] imagery and a 250m DEM derived from the Shuttle Radar Topography Mission (SRTM) (Jarvis, Reuter, Nelson et al., 2008) to identify previously unrecognized connections between palaeolakes located in endorheic basins in the Afar region of Africa and the Victoria River DDN of Australia (Fig. 5).

(Fig 5)

The two regions offer the opportunity to compare two very different tectonic regimes. Although Australia has been subject to widespread small-magnitude Earth movements, it is a comparatively stable cratonic platform (Twidale, 2011), while the Afar region of Africa is a highly active tectonic region. The purpose of the analysis was to identify evidence for pre-existing throughgoing drainage networks in the DDNs, and to evaluate the relative importance of climatic or tectonic/morphogenetic factors in fragmenting the former network.

Tectonic activity and syntectonic volcanism have been held to be the primary cause of basin closure, with exogeneic geomorphic processes acting as important secondary causes (Currey and Sack, 2009). Tectonism and volcanism can produce endorheism by either blocking basin outlets or lowering basin floors, while exogenic geomorphic processes usually embellish pre-existing structural features (Currey and Sack,

2009). DDNs can be used to interpret the relative importance of climatic vs. tectonic/geomorphic factors in the production of internal drainage, based on the presence or absence of tectonic and morphogenetic features and of evidence for former connectivity.

1 Case study methodology. In both case studies, the first step of the process was to identify and merge together those basins which appeared to be former subbasins of a larger pre-existing palaeolake. This was done by redoing the streamflow and closed contour area generation within a higher resolution 250m DEM and merging together those basins which shared a spillover point (lowest point on the basin boundary) with another basin, since those basins are interpreted to represent the splitting of a former, larger palaeolake into smaller subbasins upon the onset of internal drainage. The process was repeated until all wind gaps were either coincident with or located relatively near the basin border minimums.

Next, the intersection points (hypothetical wind gaps) of the streamflow segments with the basin boundaries were examined with Google Earth, ESRI imagery, and the highest resolution DEM available (SRTM 90m) for evidence of former intrabasin connectivity, including:

- Relict stream channels or stream valleys across the basin divide identified from Google Earth imagery and/or contours in the DEM;
- Structural conduits for potential hydrologic flow at the wind gap, such as saddles between hills or fault-bounded channels;
- Trains of small water bodies along the streamflow lines (indicates possible former stream or water body);
- Low point of basin located close to wind gap (indicates basin is sloped toward spillover point);

Each basin was then examined for evidence of structural deformation and morphogenetic influence, including:

- Fault scarps, alluvial fans, or volcanic features on intrabasin divides.
- Palaeoshorelines lower than or tilted relative to outline of closed contour area topographic depression (indicates basin lowering or deformation). The average elevation of the boundary of a closed contour area was assumed to be its palaeoshoreline; and

- Karst topography.

Finally, the ratio of the different evidences for each basin was used to assess the relative importance of climatic vs. tectonic/morphogenetic factors in contributing to topographic closure for that basin. For example, a relict stream valley across the basin divide and a palaeoshoreline higher than the wind gap indicate former connectivity undistorted by tectonic influences, suggesting that climatic influences played a major role in inducing closure in a formerly open basin. Conversely, the location of a hypothetical wind gap on an unbroken fault scarp of a deep basin and a palaeoshoreline lower than the wind gap would indicate the absence of former connectivity, suggesting that tectonic forces were the major influence in producing a basin which was never open to external drainage. In this case, the wind gap is a theoretical by-product of the streamflow generation process, and was never the location of an actual exit for drainage from the basin.

Applying this reasoning to all basins within a DDN “reverse engineers” the process of basin closure within a DDN, and produces a drainage model which, though simplified, can be used as a basis for more detailed investigation. It should be noted that the drainage networks presented here are not located within a timeframe, and by themselves are not amenable to dating the onset of internal drainage. It is probable that the onset of internal drainage was diachronous in many basins. Combinations of stratigraphic reasoning with other studies such as isotope analysis, coring, or well and seismic studies can help address such issues.

V African and Australian lakes case studies

1 The Afar triangle, Africa

In northeast Africa, the levels of palaeolake shorelines in closed basin settings have been extensively used as benchmarks for climate change (Forman, et al., 2014; Garcin, et al., 2012; Ghinassi, et al., 2012, 2015). These lakes are located primarily in craters or fault-bounded basins, whose steep sides allow lake level changes to be easily observed. They are regarded as one of the best sources of palaeoclimatic data because their water balances are considered to be almost wholly a function of climatic factors, though tectonic factors may also have had an effect (Goerner, et al., 2009; Sagri, et al., 2008; Schütt and Busschert, 2005; Zenebe, 2009).

Located primarily within the country of Ethiopia and neighboring Djibouti, the Afar region contains several of the most widely-studied closed-basin lakes in Africa. The Afar is also one of the most hostile

environments on Earth, with temperatures averaging around 34°C and annual precipitation of less than 100 mm/year, mostly in the form of torrential rainfall (Cieśluk, et al., 2014; Molin and Corti, 2015; Varet, 2010). Additionally, the location of the port town of Djibouti on the Red Sea has made it strategically important for combating terrorism, and several international military facilities are based there, including Camp Lemonnier, the primary base of operations for the U.S. in Africa (Shinn, 2004). Although Djibouti has not experienced the protracted violence of neighboring Somalia, a suicide bombing occurred in 2014 (stripes.com, 2014), and tourists have been abducted and killed while traveling the interior (Cieśluk, et al., 2014). A DDN analysis of the Afar closed-basin lakes, therefore, has the potential to economically and safely obtain information which may be more difficult to acquire through traditional fieldwork-based studies.

a *Geographic setting.* The Afar region of northeast Africa is one of only two places in the world where oceanic rift systems come ashore, the other being Iceland (Stein et al., 1991). The Gulf of Aden rift propagates westward into the Afar depression through the Gulf of Tadjura and the Ghoubbet Strait, while the Red Sea rift comes ashore in the north. The two major rift arms overlap without direct connection, resulting in complex, distributed deformation and extension accommodated by dike intrusions and normal faulting. (See Corti, et al. (2015) for an overview of the tectonic history of the region).

Geographically, the Afar is a triangular region of low elevation bounded by high plateaus, and is located at the northeastern termination of the Main Ethiopian Rift (MER), a fault-bounded corridor which extends about 1,000 km from the Afar to the Turkana depression (Corti, 2009; Corti, et al., 2015). The Afar landscape is dominated by fresh fault scarps and volcanic edifices created during episodic volcanic, volcano-tectonic, and purely tectonic events (Corti et al., 2015). The main stream draining the Afar region is the Awash River, which is well-known for the important hominid finds along its banks (Cieśluk, et al., 2014). It rises in the central portion of the MER and terminates in Lake Abhe near the Gulf of Tadjoura.

b *The Afar DDN.* The DDN that encompasses the majority of the Afar region originates in Lake Awassa at the highest elevation of the MER, and then drops gradually to the Afar triangle (Corti 2009; Olaka et al., 2010). It contains 31 endorheic HydroBASIN subbasins ranging in size from 21 to 99,693 sq km, and one small exorheic basin of 442 sq km through which the generated streamflow from the DDN exits into the Tadjoura

Gulf (Fig. 5A). Within the DDN are 40 closed contour areas, of which 23 contain water bodies or salt playas in remote imagery, and 17 are topographic depressions.

c Lakes in the Afar DDN. Within the Afar DDN, Lakes Abhe and Asal near the Gulf of Tadjoura and the Ziway-Shala lake system in the southern portion of the MER have all been the focus of palaeoclimatic studies (Fig. 5A). The lakes are located in separate endorheic basins, connected hydrologically by NE-SW aligned regional faults (Alemayehu, et al., 2006):

- The Ziway-Shala lake system consists of four closed-basin lakes situated within a caldera complex in the highest portion of the MER (Corti, 2009; Olaka, et al., 2010; Vallet-Coulomb, et al., 2001). Studies have confirmed the existence of a former megalake that connected all four lakes, which periodically overflowed into the Awash River (Benvenuti, et al., 2002; Grove, et al., 1975; Nyssen, et al., 2004; Olaka, et al., 2010; Sagri, et al., 2008).
- Lake Abhe is a saline lake located in the fault-bounded Tendaho graben approximately 75 km west of the Gulf of Tadjoura. The lake, whose name means “rotten” in the local language, contains geothermal features such as hot springs, methane-hydrogen sulfide emissions, and travertine towers, and like the Ziway-Shala system, was once a subbasin of a megalake which covered most of the Tendaho graben (Gasse, 1990). Because the lake directly registers rainfall fluctuations on the neighboring plateaus through flow received from the Awash River, it has been frequently used as a climatic indicator (Forman, et al., 2014; Gasse, 1990, 2000; Ghinassi, et al., 2015; Nyssen, et al., 2004).
- Lake Asal is the lowest dryland site on the African continent, and Africa’s most saline lake. It lies at an elevation of about -150m, which persists because a volcanic sill known as Goubbat-al-Karab (“navel of the world”) separates it effectively from the Gulf of Tadjoura (Rugescu et al., 2010). The lake lies within a tear zone between overlapping fault zones, with rifting dominated by steeply dipping dikes and faults (Manighetti, et al., 2001; Stein, et al., 1991). The water in the lake is derived predominantly from hot springs fed directly by gravity from the Red Sea, and is nearly ten times more saline than the nearby Gulf of Aden (Rugescu, et al., 2010). Because its only hydrologic connection to the Awash basin is groundwater circulation, Lake Asal has not been used as a proxy for palaeoclimatic conditions (Gasse,

1990; Nyssen, et al., 2004; Stein, et al., 1991). The following DDN analysis, however, suggests that an aboveground hydrological connection once existed between Lake Asal and the Awash system.

d Afar DDN analysis. The process of merging subbasins, repeating streamflow and closed contour area generation, and evaluating individual basins for climatic vs. tectonic/morphogenetic closure produced nine sub-networks (sub-DDNs) that exit the Afar DDN through Lake Asal, and one basin with no evidence of downstream connectivity³ (Fig. 6). The largest sub-DDN (shaded green in Fig. 6) is an integrated cascade of hydrologic connections from Lake Awassa at the head of the DDN to Lake Asal and the Gulf of Tadjoura.

(Fig. 6)

While the geologic framework of the region precludes the complete elimination of tectonic factors during the fragmentation of the networks, there is evidence that climatic causes may have played a primary role in the largest basin in the Afar DDN, which contains Lake Abhe and the watershed of the Awash River (Basin #1-3 in Fig. 6). The closed contour palaeoshoreline of Lake Abhe is higher than the hypothetical wind gap at the streamflow spillover point, and a dry stream bed is clearly evident in remote imagery at the wind gap (Fig. 7, lower left). Four basins outside the Awash watershed (cross-hatched in Fig. 7A) also received an endorheic closure rating of primarily climatic because there were dry stream beds at the wind gaps and/or the wind gaps were lower than the level of the palaeoshoreline. However, since the only sources of inflow for these basins are groundwater and meteoric waters, it is reasonable to question whether these potential palaeolakes reached the same depths as those along the Awash River, especially since inflow infiltrates quickly into the basalts due to open faults (Haga, 2012). Further study may help to confirm the existence of palaeoshorelines in these areas, as well as in the other sub-DDNs not in the path of the Awash River.

(Fig. 7)

³ Endorheism causation analysis available in table form in supplementary files.

The topographically highest basins in the Afar DDN contain Lake Awassa and the Ziway-Shala lake systems, and received mixed climatic-tectonic closure ratings, even though they are volcanic caldera lakes, because of well-defined relict palaeochannels across the basin borders (Fig. 8). Only one basin appears to have no evidence of former connectivity (see circled area in Fig. 7 for location). Consisting of a fault-bounded depression with a salt lake in Google Earth imagery (Fig. 7, lower right), the basin has no closed contour area and no apparent exit channels, and so is interpreted to have never had hydrologic connection with another basin. However, this hypothesis rests on the assumption that the current fault scarps bounding the basin have maintained their current position since onset of faulting, and it is possible that renewed faulting destroyed a previous channel for drainage from the salt lake.

(Fig. 8)

e Timing of stream network fragmentation. While the DDN analysis suggests that a former integrated stream network existed along the entire MER from Lake Awassa to the Gulf of Tadjoura, the streamlines themselves do not provide evidence that the entire network was ever hydrologically active along its whole length at any one point in time, and the onset of internal drainage may have been diachronous across the DDN.

In the southern portion of the Afar DDN, Sagri et al. (2008) constrain the final avulsion of the Awash River away from the Ziway-Shala lake system to the early Holocene (10-5 ky BP), attributing it to the opening of the Afar depression and eastward tilting of the MER valley floor. Within the Afar depression, Gasse (1990) dated the final decline of the Lake Abhe palaeoshoreline beginning around 4.5 ¹⁴C years BP (Table 2, Fig. 9). Lake Asal, on the other hand, dropped from 160m asl to almost its current level about 6 ¹⁴C years BP, rose about 140m to -15m asl around 5 ¹⁴C years BP, and then dropped again to its current level of -155m after 4 ¹⁴C years BP. The rapid decline of Lake Asal prior to the drop of Lake Abhe suggests a disconnect between the two events, and Gasse and Fontes (1989) hypothesize a tectonic event that triggered sudden seepage to the sea through recently opened fractures. The continuation of streamflow from Lake Abhe and the adjoining palaeolakes may have helped to refill Lake Asal after the first sudden decline, until increasing aridity dropped Lake Abhe's water level below the Hanle sill at around 4.5 ¹⁴C years BP and triggered the onset of internal drainage in the Hanle, Gaddale, and Asal basins. Stratigraphic studies and shoreline analyses on the intervening

basins between Lake Abhe and Lake Asal may help to refine the timing of the fragmentation of the stream network.

(Fig. 9)

Table 3. Published palaeoshoreline levels for Afar palaeolakes.

2 *Victoria River DDN, Australia*

The Victoria River DDN, located primarily in the Northern Territory, but also extending into Western Australia and South Australia, is relatively stable, both politically and tectonically, when compared to the Afar DDN.

The combined exorheic and endorheic basins of the DDN comprise about 9% of the total area of the Australian continent (Geoscience Australia, 2018). Within the DDN are 101 endorheic basins and the exorheic basin of the Victoria River, which drains into the Joseph Bonaparte Gulf (Fig. 5B). The analysis here is concerned only with the endorheic basins, which constitute about 85% of the total area of the DDN.

a *Geographic setting.* The Northern Territory of Australia makes up one-sixth of the Australian continent, but contains only 1% of the country's population, with the majority living in the northern port city of Darwin. (Australian Bureau of Statistics, 2016; Geoscience Australia, 2018). Mining and mineral extraction are major industries in the DDN, including the Northern Territory's most economically important gold deposit (Ahmad and Scrimgeour, 2013). The famous geologic landmark of Uluru, formerly known as Ayers Rock, is located near its southern border.

The endorheic basins of the Victoria River DDN are under the dominance of the subtropical high pressure belt, and rainfall is highly variable and infrequent, with most rain occurring during the summer months (<http://www.bom.gov.au/climate/>). Major geographic regions include semi-arid grasslands and the Tanani and Central Australian desert (Magee, 2009). The climate is semi-arid, with mild winters and very hot summers (Paltridge, 2002).

b *Lakes in the Victoria River DDN.* Australia's lakes are useful analogues for Pleistocene hydrologic change and evaporite formation, offering the potential for long records of palaeohydrologic changes, and are also potential sources of mineral commodities (Bowler, 1995; Magee, 2013; Hou, Michaelsen, Keeling et al.,

2014; Mernagh, Bastrakov, Jaireth et al., 2016). The Australia Geosciences Surface Hydrology Database (Geoscience Australia, 2018) shows 146 named and 4,867 unnamed lakes in the Victoria River DDN, of which only about 6% are perennial. Unnamed water bodies are far smaller than named water bodies, averaging about .33 sq km, while named water bodies average 38 sq km. Ten non-perennial lakes make up 80% of the total water surface area, the two largest of which are Lake Mackay and Lake Amadeus, accounting for about 40% of the 8,840 sq km of water surface area within the DDN.

Noteworthy lakes within the DDN (Fig. 5B) include Lake Amadeus, the prominent water body in the Amadeus basin, an anticlinal depression with a collapsed core due to solution of upthrust evaporite deposits (Magee, 2013); Lake Woods, a large ephemeral wetland and important conservation area that becomes one of the Australian tropical zone's largest temporary freshwater lakes during periods of major flooding, (nt.gov.au, 2018); and Lake Mackay, a major salt lake that may have evolved from the collapse of a former salt diapir (English, Lewis, Bell et al, 2012).

In addition to salt lakes, the Victoria River DDN contains an extensive network of palaeovalleys, which are an important groundwater resource for Aboriginal communities, horticultural and tourism enterprises, and mining operations in the Tanami region (English et al., 2012). Palaeovalleys are also prospective sites for sandstone-uranium deposits and alluvial gold and diamond placer deposits (English, Lewis, Bell et al., 2012).

c Victoria River DDN analysis. The process of merging basins and re-generating streamflow and closed contour areas within a higher resolution DEM produced 80 merged basins and 82 closed contour areas, with 35 of the closed contour areas corresponding to lakes in the Surface Hydrology Database. Of the remainder, twenty-five contained traces of former lakes such as salt playas or areas of darker vegetation visible on Google Earth[®], and 21 were topographic depressions without visible signs of former water bodies.

The Victoria River DDN is very flat, with both total relief and average slope an order of magnitude less than the Afar region. Unlike the Afar DDN, the majority of Victoria River basins appear to have undergone topographic closure primarily from climatic factors, evidenced mainly by the large network of relict palaeochannels throughout the DDN. Although basalts occur in the stratigraphy of the area (Wilford, 2003), there are no recent volcanic features, and no karst features.

The endorheic basins of the Victoria River were divided into seven sub-DDNs based upon their average elevation. As with the Afar DDNs, basins were listed within each sub-DDN from highest elevation to lowest, based upon the decreasing height of their streamflow intersection points (hypothetical wind gaps). The sub-DDNs also contained the watersheds of the largest ephemeral streams in the DDN.

The basins were ranked for the importance of climatic vs. tectonic-morphogenetic factors primarily upon the presence or absence of well-defined palaeovalleys in the DEM, most easily visualized by coloring elevation values with repeating shades of contrasting colors at short elevation intervals (Fig. 13). Faults from a Geoscience Australia dataset that were located near wind gaps were also noted as possible tectonic features that may have influenced basin closure⁴.

A literature search could find only two published palaeoshorelines within the DDN: Lake Woods (216-220m) (Bowler, Duller and Perret, 1998) and Lake Lewis (560m) (English, Spooner, Chappell et al., 2001). Both agreed strikingly with the palaeoshorelines calculated from the average elevation of the closed contour area boundaries (558m for Lake Lewis and 218m for Lake Woods). Additionally, Lake Gregory to the west of the DDN has a published palaeoshoreline of 295m (Veth, Smith, Bowler et al., 2009), which also matches the palaeoshoreline calculated from the closed contour area, giving confidence to the assumption that the borders of the closed contour areas in the DDN are good approximations of former palaeoshorelines.

The range of differences in elevation between the calculated palaeoshorelines of the closed contour areas and the hypothetical wind gaps of the basins in which they were located was 13m, which is much narrower than the Afar value of 84m. The wind gaps are on average only about 3m higher than the closed contour areas, which is interpreted to mean that the palaeoshorelines of the closed contour areas in the Victoria River DDN are very close in height to the former spillover points of the basins, showing that little tectonic movement has distorted them. For purposes of ranking climatic vs. tectonic factors in causing basin closure, all closed contour areas with calculated palaeoshorelines equal to or greater than the wind gap elevation minus 3m (average difference) were considered to be equal to or greater than the elevation of the wind gap

⁴ Endorheism causation analysis available in table form in supplementary files.

The final result was an integrated stream network with strong evidence of throughgoing connectivity, separated into seven different sub-DDNs delineated mostly by elevation changes (Fig. 10). Streamflows within the highest sub-DDNs proceed westward from Lake Lewis and the Lake Amadeus basin into Lake Mackay, then continue north through continuously lower sub-DDNs into the area around Lake Woods, where they enter the Victoria River exorheic watershed.

(Fig. 10)

Profiles of the two longest DDN streamflows reveal that a series of mostly concealed E-W trending faults mark major elevation changes and breaks in slopes (Raymond, Liu, Gallagher et al., 2012) (Fig. 11), suggesting a possible role for tectonic movement in the process of basin closure and divide migration.

(Fig. 11)

One of the most striking feature of the DDN analysis was the conformance of the derived streamflow to two groupings of palaeovalleys which are very obvious in the shaded DEMs, but almost undistinguishable in remote imagery. The higher, southern palaeovalley system has been noted by many researchers (Magee, 2009; English, Lewis, Bell et al., 2012; English, 2016; Mernaugh, Bastrakov, Jaireth et al., 2016; Sandiford, 2009; Brocard, Ding, Salles et al., 2017). This system is included in a GIS database of palaeovalleys created by Geoscience Australia and encompasses the DDN streamflows within the five highest sub-DDNs (Fig. 12). Interestingly, the DDN streamflow flows N-NE, but the configuration of the palaeovalleys suggest that the original drainage was westward across a former divide. This is also supported by the overlap into the DDN of a westward-draining palaeovalley system that eventually exits to the North West Shelf (English, Lewis, Bell et al., 2012; Brocard et al., 2017) (Fig.12).

(Fig. 12)

This suggests three possible basin closure scenarios:

- Passive closure, resulting from decreased precipitation lowering streamflow enough so that pre-existing basement structure served to block through-flowing drainage;
- Active closure resulting from large wavelength tectonic movements, such as downwarping of basins (Magee, 2009), or the back-tilting of the Australian continent to the south described by Sandiford et al.

(2009), which combined with decreased precipitation to behead formerly north and northwest-flowing drainages; or

- A combination of passive and active closure scenarios.

The northern, lower elevation sub-DDN contains a network of well-defined anastomosing palaeovalleys which does not appear to have been previously reported, with accordant wind gap elevations ranging between 210-250m asl (Fig. 13). The palaeovalley system appears to originate in the Tarrabool-Sylvester Lake system and flow west, where it is joined by DDN streamflow from the southern, higher palaeovalley. The DDN streamflow then continues into the exorheic Victoria River watershed through a well-defined palaeovalley. Because of the anastomosing nature of the palaeovalleys, it is probable that the DDN streamlines represent only one of several possible configurations of former streamflow through the network.

(Fig. 13)

d Timing of stream network fragmentation. Most researchers have dated fragmentation of the Australian palaeovalleys to the Cenozoic. English, Lewis, Bell, et al. (2012) used pollen in sediments and stratigraphic correlation to date basal palaeovalley sediments to the Eocene, which would provide a maximum age for drainage fragmentation. Brocard, Ding, Salles, et al. (2017) estimate that aridification was well advanced in Western Australia well before the Quaternary, and possibly as early as the Middle Miocene. Wilford (2000) dated diversion of palaeovalleys in the Tanami area to the mid-Miocene as well.

It is possible that the onset of endorheism was diachronous across the DDN, especially since mean annual rainfall currently increases from the south to the north. If so, the end of throughgoing drainage in the DDN may be bracketed by the period of aridity that led to the drying up of Lake Woods and, presumably, the anastomosing palaeovalley system in which it is located. The start of this arid period has been dated to around 35ka (Hesse, Magee and Van Der Kaars, 2004).

A halotectonic origin has been proposed for several of the lakes in the Victoria DDN, including Lake Mackay, Lake Hopkins, Lake Neale and Lake Amadeus (English, 2015). Under this scenario, former diapirs of ancient evaporites penetrated the landscape surface in the Late Cenozoic, and topographic lowering and salt lake development occurred as the diapirs began to collapse and dissolve.

VI Comparison & areas for future investigation

The two DDN analyses contrast different styles of endorheic basin closure within passive and active tectonic regimes. In the Afar DDN, tectonic-morphogenetic influences on basin closure dominate, while in the Victoria River DDN, climatic factors appear to dominate. However, tectonic influences appear to have played a part in the Victoria River DDN as evidenced by the existence of concealed faults and the diversion of palaeovalleys, while a decline in precipitation appears to have played major part in inducing endorheism in the Awash River watershed, the largest basin of the Afar DDN. It appears, therefore, that both climatic and tectonic factors can play important roles even in basins dominated by one particular tectonic regime.

The analyses also suggest the possibility of throughgoing drainage networks in both DDNs. In the Afar region, there appears to have been a previously unrecognized hydrologic connection from Lake Awassa to the Gulf of Tadjoura. In the Victoria River, DDN a previously unreported palaeovalley system in the northern part of the DDN appears to have been joined by a recognized palaeovalley system located in the southern part of the DDN that migrated away from a northwesterly drainage direction, possibly due to long-term lithospheric buckling (Sandiford et al., 2009).

Areas exist for further investigation in both DDNs. The Afar analysis increases the inventory of potential palaeolakes in the Afar region and the MER, since each closed-contour depression generated during the analysis has the potential to represent a former lake. Changes in palaeolake levels are some of the most important proxies for climatic change in northeastern Africa (Lamb, et al., 2002), and further studies may shed more light upon the distribution and interconnections of palaeolakes in northeastern Africa. The Victoria River DDN analysis reveals a previously unrecognized palaeovalley system which may represent a source of much-needed groundwater and may additionally be prospective for evaporative minerals and alluvial uranium or gold. The multi-color DEM contour analysis can be used to increase the understanding of the configuration of palaeovalleys by resolving their contours on a higher scale.

The DDN analysis model described here can be easily applied to any of the DDNs identified in this work. For those familiar with the GIS program ArcGIS, a similar process described by Breeze, Drake, Groucutt et al. (2015) for the Arabian peninsula offers a comparable methodology.

One intriguing possible application would be extending the DDN model to palaeo-flow paths on planetary surfaces. Unless there is digital elevation data available, however, the process would likely involve visual inspection to determine both the boundaries of planetary endorheic basins and any erosional or tectonic/morphogenetic features at the basin divides.

Another application would be a combination of DDN analysis with the vast geospatial datasets and cloud-computing capabilities of Google Earth Engine (Alonso, Muñoz-Carpena, Kennedy, et al., 2016; Gorelick, Hancher, Dixon et al., 2017). Google Earth Engine (GEE) is a cloud-based platform designed to give researchers the ability to analyze and perform computations on very large geospatial datasets without the need for extensive technical training (Gorelick, Hancher, Dixon et al., 2017). Available datasets include remote sensing imagery from many MODIS datasets and the entire LANDSAT archive, as well as elevation data and precipitation, sea surface temperature and other environmental datasets. (A detailed introduction to utilizing Earth Engine can be found at <https://www.google.com/earth/outreach/learn/introduction-to-google-earth-engine/>).

GEE can be accessed with limited functionality through a public browser interface, or with more functionality through free registration as a researcher. The first method allows any user to pull layers of datasets from GEE's data catalog into a browser interface similar to that of Google Earth, with layer names displayed on the left and the actual data overlain on a Google Earth view on the right. Using this method, for example, it is possible to visualize data in a time lapse series, by having different layers of the same dataset in the workspace, with each layer set for a different time (Fig. 14).

(Fig. 14)

Further capabilities are enabled by registering for access, which gives the ability to import data into GEE and to utilize GEE's computation ability on a first-come first-serve basis. One example of how DDNs could be integrated with GEE is discussed below.

a Caspian Sea level rise

Between 1977 and 2005, the Caspian Sea was subject to a rapid rise in sea level (Leroy, Tudryn, Charlie et al., 2013). While the exact cause is still in question, it is generally thought that water level fluctuations of the

Caspian Sea are the result of climate-induced changes in the hydrological budget, with tectonic causes and deep groundwater flows from the Aral Sea also thought to be factors (Roshan, Moghbel and Grab, 2012; Chen, Pekker, Wilson, et al., 2017).

In India, the former palaeochannel of the Sarasvati River has been demonstrated to transport moisture from the sub-Himalayas to the Thar desert (Mitra and Bhadu, 2012). The configuration of the Uzboy River DDN (Fig. 2e) raises the possibility that a similar palaeochannel groundwater transport system may exist between the Caspian Sea and the vast endorheic basins of the Himalayan plateau. Intriguingly, a major high-level phase of the Caspian Sea has been linked to abundant flow from the Uzboy River at ca 4 ka (Leroy, Marret, Gibert et al., 2007). Google Earth Engine could be used to address this question by importing the Uzboy DDN shapefiles into a workspace and overlaying them with remote sensing imagery, snow thickness data, and a time lapse series of historical snow cover images, to discern whether a correlation exists between snow cover levels in the Himalayas and recent water level rises in the Caspian Sea.

VII Conclusion

Drainage networks are the basis for defining drainage basins, which control the connection of continental land mass to the world's oceans (Vörösmarty, et al., 2000). The onset of internal drainage within a basin may be a reflection of climate change, tectonic processes, or a combination of both. By quantifying the areal extent of internal drainage formerly contained within a watershed, and by identifying connections between endorheic and exorheic basins, the DEM-derived networks produced in this study can enable finer scales of analysis of the historical causes and processes that have led to the onset of internal drainage in different regions throughout the world.

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