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Development of a Hydrogeological Conceptual Model for Shallow Aquifers in the Data Scarce Upper Blue Nile Basin

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Abstract: Rural communities in sub-Saharan Africa commonly rely on shallow hand-dug wells and springs; consequently, shallow aquifers are an extremely important water source. Increased utilisation of shallow groundwater could help towards achieving multiple sustainable development goals (SDGs) by positively impacting poverty, hunger, and health. However, these shallow aquifers are little studied and poorly understood, partly due to a paucity of existing hydrogeological information in many regions of sub-Saharan Africa. This study develops a hydrogeological conceptual model for Dangila *woreda* (district) in Northwest Ethiopia, based on extensive field investigations and implementation of a citizen science programme. Geological and water point surveys revealed a thin (3–18 m) weathered volcanic regolith aquifer overlying very low permeability basalt. Hydrochemistry suggested that deep groundwater within fractured and scoriaceous zones of the basalt is not (or is poorly) connected to shallow groundwater. Isotope analysis and well monitoring indicated shallow groundwater flow paths that are not necessarily coincident with surface water flow paths. Characteristics of the prevalent seasonal floodplains are akin to "dambos" that are well-described in literature for Southern Africa. Pumping tests, recharge assessments, and hydrometeorological analysis indicated the regolith aquifer shows potential for increased utilisation. This research is transferrable to the shallow volcanic regolith aquifers that overlie a substantial proportion of Ethiopia and are prevalent throughout the East African Rift and in several areas elsewhere on the continent.

Keywords: conceptual model; shallow aquifer; regolith; dambo; Ethiopia

1. Introduction

The availability of groundwater in sub-Saharan Africa and its potential for agricultural use has been increasingly reported in recent years with many authors predicting that a rapid expansion in groundwater exploitation, as occurred since the 1960s in South and East Asia, may be imminent [1–4]. The use of groundwater for small-scale irrigation is increasingly promoted by governments, donors, and non-governmental organisations (NGOs) as an important tool to alleviate poverty, improve food security, boost rural employment and economic development, promote gender equality, and mitigate against increasing climate variability [5–8]. Small-scale groundwater irrigation is preferred by smallholders, where they can find the necessary means and finances, in comparison to large-scale irrigation schemes, due to the autonomy it provides and the enhanced livelihoods created by moving from subsistence to market-oriented agriculture [9,10].

Prior to promotion of groundwater irrigation in sub-Saharan Africa, we need to improve our knowledge of the aquifer systems; it is commonly expressed in the literature that the hydrogeology of the region is under-studied and poorly understood [11–13]. This view is shared by governments who could provide significant benefit to their populace in the form of interventions with such increased knowledge. For example, the Ethiopia's Ministry of Water Resources stated: "Ethiopia's hydrogeology is complex and at present only partly understood" [14]. The importance of shallow aquifers as locally important water sources is well reported; often simultaneously reported is the scarcity of observations of such groundwater systems, in particular sustained time-series data [11,12,15]. This scarcity of data contributes to poor understanding of these shallow hydrogeological systems. The Ethiopian Agricultural Transformation Agency (ATA) have recognised the importance of shallow aquifers [16] and launched shallow groundwater mapping in 2013 across selected areas in Ethiopia. The mapping is based on acquiring extensive field data of shallow aquifers, remote sensing, and modelling to promote smallholder irrigation.

Development of a hydrogeological conceptual model is key to better understanding of a hydrogeological system and is the key first step in any numerical modelling study [17,18]. A conceptual model is a set of simplifying assumptions describing the groundwater system produced by interpretation of all available information. The characteristics of the real system that are summarised include topographic and surface water information, aquifer properties and boundaries, groundwater flow directions, aquifer relationships, and water balances. Development of a conceptual model typically includes assessment of existing topographic, geological, and hydrometeorological data, which will generally require, to a varying degree depending on the study site location, being supplemented with new field investigations, laboratory analyses, and additional monitoring [17]. There is a shortage of published detailed hydrogeological conceptual model studies from sub-Saharan Africa, particularly concerning shallow aquifers [19,20]. Unfortunately, existing data on shallow aquifers to facilitate hydrogeological conceptual model development are generally scarce across a great deal of the continent, including at this study site. Therefore, field investigations had to be extensive and involved a variety of methods to take advantage of available equipment and expertise in both the field and the laboratory. It was also necessary to establish hydrometeorological monitoring to infill gaps in the existing formal monitoring networks.

This paper contributes towards building up a better picture of the continent's hydrogeology, through development of a conceptual hydrogeological model for the shallow aquifers in and around Dangila (a local administrative district), within the Lake Tana Basin in the headwaters of the Abay River (Blue Nile) in Northwest Ethiopia. The aquifers are currently exploited by most rural households, although at very low levels for domestic use and "backyard" irrigation. Backyard irrigation in the area is comparatively high as compared to many other sites in Ethiopia with potential to increase in the near future, and thus, the area is designated as a growth corridor by the government [16], which is the reason for its selection as the study site. Agriculture in the area is predominantly rainfed and it has been proposed that utilisation of shallow groundwater for small-scale irrigation could provide a second growing season delivering the aforementioned benefits to the local community [21].

Within the Lake Tana Basin, the deep Eocene–Miocene flood basalts and the overlying Quaternary basalts are well-described in the literature, in terms of recharge and flow mechanisms, isotope and hydrochemistry, and (less common) aquifer properties; this deeper geology provides the water source for the few public supply boreholes in the area (e.g., [22–24]). However, the superficial weathered layer is rarely considered, and this layer is the shallow unconfined aquifer that is utilised by rural communities via manually excavated wells. At the study site itself, a comprehensive study of the deeper Quaternary basalt aquifer was conducted by Fenta et al. [25], applying geophysical, hydrochemical, and remote sensing techniques to develop a hydrogeological conceptual model. The authors noted that improved knowledge of the overlying regolith was required to give a more complete picture of the hydrogeology. Conceptual models of the Quaternary basalt hydrogeology were also developed by Nigate et al. [26] who investigated large public supply springs in the Gilgel Abay catchment (the major tributary of Lake Tana), within which is located most of the Dangila study site. Again, the shallow regolith aquifer that feeds abundant low discharge and often seasonal springs utilised by rural communities was not investigated. Moreover, abundant hydrological modelling studies exist for the Gilgel Abay catchment to better understand catchment behaviour (e.g., [27]) or more often describing likely future impacts of climate change (e.g., [28–30]) and of land cover change (e.g., [31–33]) with neither investigation nor consideration of the shallow hydrogeology with which the hydrology is inexorably connected.

Our definition of shallow aquifer is an aquifer with depth of <25 m. Although there are exceptions around the world, 25 m is considered the maximum feasible depth of excavation of "hand-dug" wells [34,35]. Furthermore, much of the existing small-scale groundwater irrigation in sub-Saharan Africa depends on a water table depth of less than 5 m because of power limits on water-lifting and because of available technology; motorised pumps are much less common than manual lifting methods in the region, used in less than 20% of water-lifting cases, due to smallholder farmers' lack of capital and ability to obtain credit [2]. Therefore, groundwater irrigation is restricted to shallow hand-dug wells for poorer farmers; depths of 50 m—the definition of shallow by some authors—cannot be regarded as easily accessible for small-scale irrigation. The predominance of consolidated and crystalline bedrock across sub-Saharan Africa restricts the potential locations for manual well excavation. However, when it is considered that regolith overlies a great deal of the crystalline basement and more recent volcanics, notwithstanding the unconsolidated sediments that cover approximately 25% of Africa [36], the extent of the shallow geology with potential for manually excavated or manually drilled wells that may support small-scale irrigation becomes pervasive [37].

This study targets a research gap that has been often identified by others: insufficient understanding of shallow aquifers in sub-Saharan Africa and uncertainty over their potential for productive use. The research aim, therefore, was to develop a hydrogeological conceptual model. Future modelling studies should also investigate the potential impacts on shallow groundwater and surface water of climate variability and land use land cover (LULC) change, e.g., land degradation and conversion of pasture or forest to arable land. Again, a hydrogeological conceptual model is a necessary preliminary step in such studies.

This paper is part of a series derived from research at the study site since 2014. Previous publications include: confirming the data quality from the citizen science hydroclimate monitoring programme [38], conducting pumping tests in shallow hand-dug wells [39], insights gained from a comparison of recharge estimation techniques [40], and a discussion on the potential for shallow aquifers to sustain small-scale irrigated agriculture [21]. While this paper draws on those earlier works, the majority of the investigations and development of the conceptual model are presented here first. In terms of geology, topography, climate, and level of socio-economic and agricultural development, the study site is considered representative of a wide area of upland Ethiopia. In particular, the location was chosen to represent an important type of shallow aquifer. Aquifers considered "shallow" and "very shallow" have a wide distribution within Ethiopia, underlying approximately 50% of the country [23].

2. Study Area

Dangila *woreda* (district) lies approximately 70 km southwest of Bahir Dar in Northwest Ethiopia and has an area of approximately 900 km^2 (Figure 1). The site ranges in elevation from around 1600 m to 2400 m, mostly comprising low hills and expansive floodplains. West of the central hills drains to the Beles River, while the east drains via the Gilgel Abay River into Lake Tana; the Beles and Lake Tana are both part of the Blue Nile, or Abay, River Basin. Dangila *woreda* has a population of around 175,000, of which 140,000 are rural [41]. Most of the 35,000 urban population reside within Dangila town. Crop–livestock–mixed subsistence farming is the primary source of livelihood. Seasonally inundated floodplains/grasslands are utilised as pasture with mixed cropping and dwellings occupying the adjacent slopes. Natural woodland is generally only found around hilltop churches and along more steeply sloping riparian strips. *Eucalyptus* plantations have been noticeably expanding throughout the duration of the project on land previously cultivated for food; a situation identified across the Lake Tana Basin despite local knowledge of the negative impacts of soil fertility and water consumption [42,43]. The higher and steeper mountains often have thin soils and are covered with low scrub-like vegetation. Rainfed agriculture predominates with the main crops of teff (*Eragrostis tef*), maize, barley and millet together making up 90% of the area coverage [44]. Very small-scale (<0.25 ha) "backyard irrigation" exists and is seen as important in terms of both cash income and household nutritional benefits; irrigated crops are generally vegetables and fruits, such as onions, chilli peppers, and coffee. Potential exploitation of the shallow aquifer for small-scale irrigation, as assessed in this research, would be to support a second growing season across a wider area following the main rainfed growing season harvest.

The mean annual total rainfall is 1640 mm, as measured (since 1988) at the Dangila National Meteorology Agency (NMA) weather station, 91% of which occurs during May to October (Figure 2). The region experiences high interannual variability in rainfall, with historical annual rainfall totals since 1980 ranging from below 900 mm to over 2000 mm. The mean annual potential evaporation is 1230 mm.

The geology of the area predominantly consists of Quaternary basalt and trachyte above Eocene–Oligocene flood basalts and trachyte [45]. The thinly bedded and often scoriaceous basalts and trachytes were erupted from relatively small and local Strombolian volcanoes 10,000 to 1 million years ago and cover a large area south of Lake Tana. The underlying flood basalts cover 25% of Ethiopia's land surface and are an example of mantle source continental flood volcanism [23,46,47].

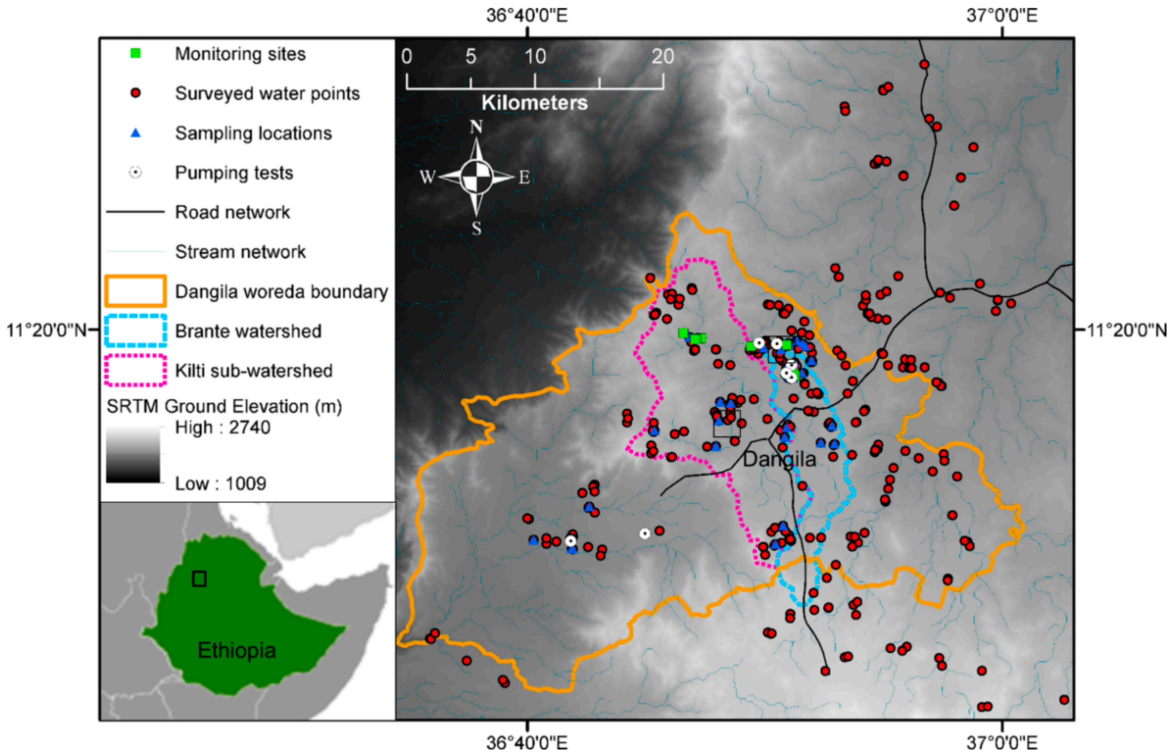

Figure 1. Location map of the study area showing monitoring sites, surveyed water points, and sampling locations. The black boxes show the locations of Figure 7a and Figure 8b (eastern box) and Figure 8a (western box).

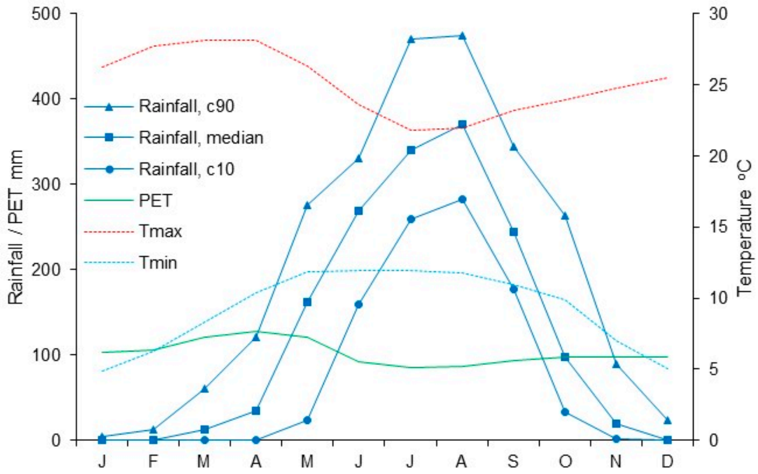

Figure 2. Monthly median, 10th and 90th percentile rainfall, mean potential evapotranspiration, and maximum and minimum temperatures as measured (since 1988) by the National Meteorology Agency (NMA) at Dangila weather station.

3. Materials and Methods

3.1. Methodological Framework

The framework presented by Brassington and Younger [17] was followed in order to further the aims of that study in standardising hydrogeological conceptual model development. It has been continually stated that hydrogeological conceptual model development should be systematic and comprehensive [18,48,49], though there have been few attempts to standardise an approach. Guidance exists within grey literature and textbooks essentially promoting the same steps of analysis of available data, field investigations and monitoring in order to evaluate aquifer properties, geometry and relationships, recharge and other fluxes, and water quality. The framework by Brassington and Younger [17] synthesised these previous works into a standard procedure. The stages involved are listed on the right of Figure 3 along with the approaches involved in each stage. While the overall methodological progress is downwards as the arrow shows, the "desk study"-to-"conceptual model" stages often occurred simultaneously. Detailed methodology of the field investigations, which took place during the wet and dry seasons between 2014 and 2018 (five visits), and subsequent analyses are presented below.

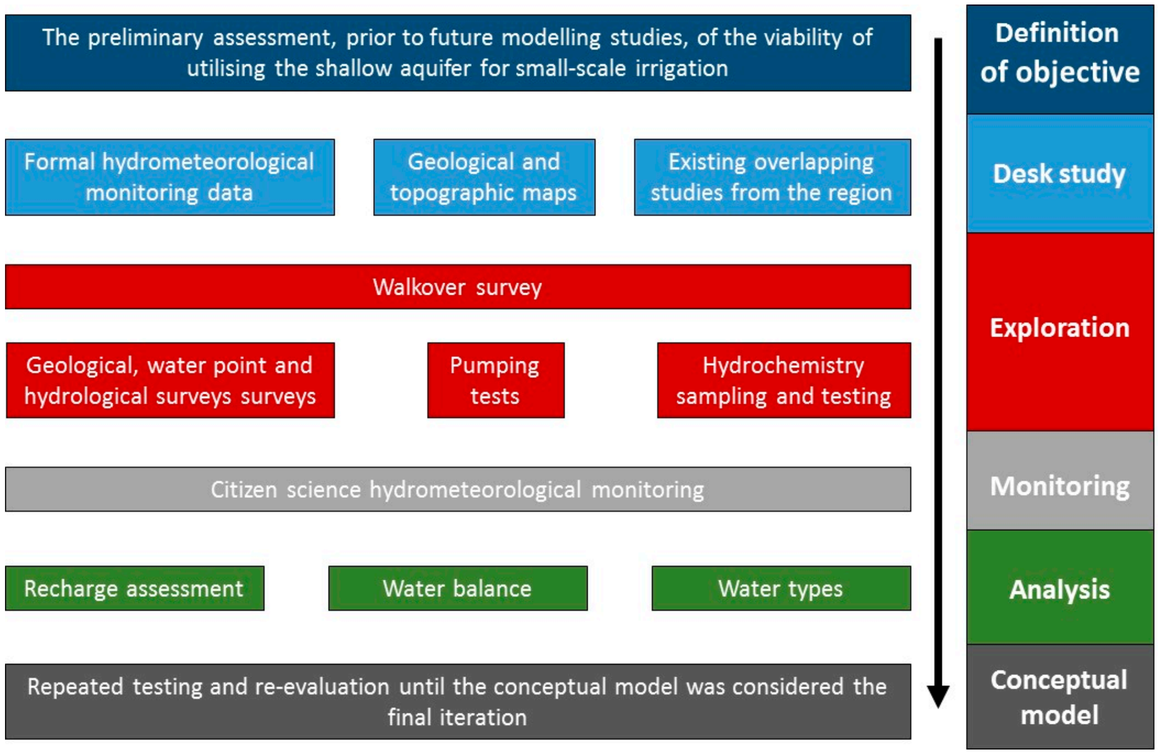

Figure 3. Methodological flowchart showing the stages (right) and corresponding methods involved in developing the conceptual model (adapted from Brassington and Younger [17]). While there is a general progression from top to bottom, many of the methods were applied simultaneously or out of chronological sequence (as indicated by the final box: "Repeated testing and re-evaluation ... "). For example, citizen science hydrometeorological monitoring occurred throughout the project beginning immediately after the walkover survey and was continually analysed as data were received.

3.2. Geological, Water Point and Hydrological Surveys

Bedrock geology was investigated at the visible outcrops in riverbeds, occasionally on steeper slopes and in a few man-made excavations. Overlying regolith was observed in well bores, excavated well materials, and riverbanks.

Water point surveys involved: accurate location, depth and water level measurements (wells and boreholes), flow rates (springs and rivers), river stage and channel incision, description of geology, topography, land use, pump/lifting device and cover (wells), in-situ measurement of water temperature, pH and electrical conductivity (EC), and discussions with the local community about the water point's use, seasonality, and history. Over 180 shallow hand-dug wells were surveyed, in addition to over 65 springs and over 90 river locations; several rivers were walked over their entire length and 10 deep borehole logs were viewed from the Dangila Town Water Supply Office. These water points were distributed throughout the study site and deliberately targeted to give full coverage of upper, mid, and lower portions of watersheds with varying topography, land cover, and geology. Locations of the surveyed water points are shown in Figure 1. The aim was not to survey every water point, which would be excessively time-consuming and difficult to confirm because they are not mapped, rather to assess a representative sample of the wells, springs, and rivers in the area.

3.3. Pumping Tests on Hand-Dug Wells

Eight pumping tests were conducted on shallow hand-dug wells in order to gain information on the regolith aquifer properties. Pumping was conducted using the wells' water-lifting equipment for 15–45 min until the height of the water column was reduced by at least 10%. To abstract for longer would have been unethical due to tests being conducted during the dry season on household wells when water levels were low. Drawdown and recovery were monitored with a pressure transducer and with a dip meter. The Moench [50] and Barker and Herbert [51] methods were applied to analyse both drawdown and recovery data, respectively. These methods were selected because they were developed for large diameter wells, i.e., well bore storage is included. The pumping tests were repeated at the end of the wet season when water levels were higher. Details of the tests and analyses are presented in Walker [39].

3.4. Hydrochemistry Sampling and Testing

The sampling and in-situ testing programme involved sampling from water points (wells, springs, and boreholes), streams, wetlands, and rainfall; sampling locations are shown on Figure 1. As with the water point surveys that occurred simultaneously, sampling and in-situ testing were distributed throughout the study site and deliberately targeted to give full coverage of upper, mid, and lower portions of watersheds with varying topography, land cover, and geology. A total of 49 water samples were analysed, many of these being repeat samples from the same locations on different visits, i.e., during both the wet and dry seasons. Samples were filtered into nalgene bottles and mostly analysed in Ethiopia. Laboratory analysis involved measurement of major ions and some trace elements utilising ion chromatography (anions), atomic absorption spectroscopy (cations), and titration (bicarbonate and carbonate). Stable isotopes oxygen-18 and deuterium ($\delta^{18}O$ and $\delta^{2}H$) were analysed using laser spectroscopy. The aims were to identify water types by water quality, relative residence time, and evaporative history.

Wells were not purged to commonly proposed standards prior to sampling. Pumping tests showed that the hydraulic conductivity of the shallow aquifer is quite low and water level recovery in the wells was slow following abstraction. Given that some field visits took place during the period of highest water scarcity, it would have been unethical to attempt to purge several well volumes prior to sampling. However, sampling preferentially took place from wells that experienced frequent use or immediately following use in order for the collection of water by the local community to mimic controlled purging. Sampling preferentially took place from sealed sources that were not open to evaporation, such as handpumps, rope-and-washer pumps, and springs at the point of emergence.

In-situ testing involved measurement of pH, EC and temperature with a handheld meter (309 tests), and measurement of radon-222 concentration with a Durridge RAD7 radon meter (18 tests). Radon-222 is a radioactive decay product of uranium-238, a radioactive element that naturally occurs in the minerals of most rocks. As an inert gas, ^{222}Rn readily migrates, through advection and diffusion, into and with groundwater [52]. Groundwater ^{222}Rn concentration reaches steady state and declines rapidly upon discharge due to the short half-life of 3.8 days. Analysis of the spatial distribution of ^{222}Rn concentrations in surface and groundwater has been previously used to investigate infiltration from surface water to aquifers and groundwater discharge into surface water (e.g., [52–54]). Further detail of the hydrochemistry sampling and testing can be found in Supplementary Materials.

3.5. Citizen Science Hydrometeorological Monitoring Programme

The first citizen science programme was established in March 2014 in Dangesheta *kebele* (village), monitoring rainfall, river stage in two rivers, and groundwater levels in five wells. The high quality of the data was confirmed with comparison to formally sourced hydrometeorological data [38]. A second programme commenced in April 2017 in Abadira *kebele*, monitoring rainfall, river stages and groundwater levels in four wells.

Formal hydrometeorological monitoring data were obtained from the NMA for the Dangila weather station and from the Ministry of Water, Irrigation and Electricity (MoWIE) for the Amen and Kilti Rivers. This formal data were utilised for comparison and quality checking of the citizen science data and for calculation of potential evapotranspiration (PET) applying the Penman-Monteith FAO56 method [55]. The Penman-Monteith FAO56 method was shown by Adem et al. [56] to perform well in the Ethiopian Highlands. The monitoring data were used to assess the seasonality of and relationships between rivers, groundwater, and rainfall and to conduct water balances.

3.6. Recharge Assessment

A multi-method recharge assessment was conducted using data from the field investigations, from both the citizen science and formal hydrometeorological monitoring, and from further published sources, e.g., large-scale recharge maps [40]. Recharge estimation methods applied included baseflow separation, soil moisture balance, water table fluctuation, chloride mass balance, basin water balance, physically based modelling, and an empirical rainfall–recharge relationship.

4. Results and Discussion

4.1. Geology

The deeper basalts are variously massive, fractured and vesicular with variations occurring in short distances. The solid geology is overlain by weathered basalt regolith. The grey regolith is clayey, gravelly, often containing basalt boulders, and strong, requiring chiselling during well excavation; local communities report there are rarely problems with well sidewall collapse. Red clayey loam soils (nitisol) are common, while soils below floodplains exhibit deep and wide desiccation cracks in the dry season suggesting a high clay content (vertisol), though they also contain alluvially transported sands and gravels.

4.2. Water Points

Wells are generally dug until further excavation becomes impossible when solid geology is reached (the local community informed us that this situation is more common than digging in the dry season only to the level of the water table that may still be within regolith). Therefore, the location of rockhead can be inferred from well depth. Eighty well depths were measured for estimation of regolith thickness; more wells were visited but access for measurement, such as in the case of wells fitted with handpumps, was not always possible. In these cases, well depths were often provided word-of-mouth, though, when these depths could be checked or when repeat visits were made on subsequent field visits, there were often large discrepancies between suggested depths and between suggested depths and actual depth measurements. This could be due to the rural Ethiopian measurement of the cubit being simply doubled to give a depth in metres or the cubit measurement being mistranslated directly into metres. Consequently, we have confidence only in the well depths that we were able to measure. Well depths ranged from 1.3 to 19 m with a mean depth of 8.7 m. Wells were shallower and the regolith aquifer was thinner on floodplains; bedrock is often visible in riverbeds with typical bank height of 1–3 m. Wells were deeper and the regolith aquifer was thicker on slopes; gullies on steeper hillsides are often incised 10–15 m into the regolith. These observations are supported by the drillers' logs for the ten deep boreholes around Dangila town that show regolith thickness from 3 to 12 m overlying basalt (the Dangila Town Water Supply Office, personal communication, 27 January 2017). The logs also show 2–20 m thick scoriaceous layers occurring occasionally and inconsistently below 25 m in 50% of the boreholes and only at greater depths of >110 m in other boreholes.

Groundwater level measurements in hand-dug wells show high seasonal fluctuation. Many wells are dry in the dry season, especially those higher on hillslopes (water table >8 mbgl (metres below ground level)), while wells at the foot of slopes, especially if down-gradient of "dambos" (see later section) have groundwater available perennially. In the wet season, groundwater levels within wells on floodplains are often close to surface level and the water table is shallow (0–3 m) in most areas.

Sparsely distributed hand-dug wells lined with concrete rings and fitted with handpumps comprised 52% of the surveyed wells; these were installed by the government and are utilised for potable water. In addition, most households have one, two, or sometimes three hand-dug wells within their compound for domestic and backyard irrigation use. Rope-and-washer pumps supplied by

NGOs were fitted on 5% of the surveyed wells and only a single treadle pump was identified. The rest of the wells utilised a rope and bucket, occasionally a double-bucket pulley system, and were uncovered or covered with a clay pot, oil drum, or metal sheet.

Water point surveys also included assessment of the few boreholes in the *woreda*. Four boreholes were drilled 3–6 km northwest of Dangila town in 2009 to 150–200 m; only two were operational at the time of the field visits, abstracting 20–30 L/s (litres per second) for 10 h per day. Within Dangila town, a 209 m borehole was drilled in 2016 and an older 124 m borehole was drilled in 1985; both abstract at 3.5 L/s for 10 h per day. In the vicinity are four further boreholes (one drilled in 1973, two drilled in 1994, and one drilled in 2007, to 58–134 m) that are non-functional due to excessive yield reduction (the Dangila Town Water Supply Office, personal communication, 27 January 2017).

Springs are commonly used by the local community, both developed and undeveloped, to collect water for domestic and potable use. Flow rates vary from over 20 L/s, where water is piped to tanks to supply the towns of Giza and Chara, to unmeasurably small seepages, though often over a large area giving a combined high total flow rate that often forms streams. Where springs and seepages emerge from gullies, they commonly occur at contacts between regolith and bedrock or gravelly regolith and more solid regolith. Springs and seepages are also very common around the edges of floodplains where the regolith aquifer thins and the water table from the surrounding slopes intercepts the ground surface.

4.3. Hydrology

During the dry season, rivers often have discontinuous dry and flowing reaches. Perennial springs often form small streams, which also later run dry. Commonly, these dry or low-flow stream sections cross large flat floodplains where the rivers are losing water. Above and below the floodplains in narrower steeper valleys, there may be more substantial flow. During the wet season, floodplains become inundated. The cause is pluvial flooding and spring discharge at the floodplain margins, rather than from rivers overflowing their banks.

4.4. Dambos

"Dambos" are, as defined by von der Heyden [57], " … shallow, seasonally waterlogged depressions forming the headwaters of ephemeral and perennial streams in subtropical and tropical Africa". Dambo profiles are "primarily concave, with shallow slopes and gradients of less than 6° (usually less than 2°). The size and shape of the dambo surface in plan vary widely, with dambos ranging from several square kilometres of wide, oval wetland to narrow, tortuous structures barely 100 m in length" [57]. This definition matches the pervasive seasonally inundated floodplain landform observed in Dangila *woreda* that are clearly visible on Figure 7a and Figure 8 between the patchwork cultivated areas. Dambos at the study site range in size from around 200 m wide to over 1600 m wide (e.g., locations 5 and 7 in Figure 8, respectively). Reported dambo characteristics also match observations at the study site, such as calcic soils (characteristic of mafic rocks) with 10–20% coarse sand and 35–60% clays with a clay layer from in-situ weathering that forces soil water to discharge at the level of the dambo at dambo verges [57]. Furthermore, the evidence from Malawi described by McFarlane [58] of non-fluviatile dambo formation, by irregular lowering of land by differential leaching and subsidence following loss of regolith mechanical strength, matches observations of Dangila *woreda*, that is, many of some floodplains cross watersheds, many are endorheic and others are circular (labelled as 3, 4 and 5, and 6 in Figure 7a and Figure 8, respectively). This identification of dambo landforms is relevant to the hydrogeological conceptual model because the differential leaching and subsidence mechanism of formation may necessarily infer the presence of preferential flow paths beneath. Studies on dambos are predominantly from Malawi, South Africa, Zambia, and Zimbabwe, and though the term occasionally appears in papers concerning Ethiopia, specific dambo studies here are non-existent.

Dambo literature states that: while evapotranspiration (ET) is increased compared to its surroundings, the main outlet of a dambo is surface water flow. Floods are suppressed at the onset of the wet season as water infiltrates dry soils and closes dessication cracks, and runoff is retained within sedges. However, dambo soils quickly saturate and have no subsequent effect on storm flows. Dambos only augment dry season surface flows until mid-dry season; later in the dry season dambos and baseflow must be fed by deeper aquifers [59,60]. This latter point is apparent from the dry or low-flow reaches of the study site's rivers as they cross dambos during the dry season.

4.5. Pumping Tests

Hydraulic conductivity estimates representing the weathered regolith shallow aquifers ranged from 0.2 to 6.4 m/d (mean: 2.3 m/d, median: 1.6 m/d) in the dry season and ranged from 2.8 to 22.3 m/d (mean: 9.7 m/d, median: 6.5 m/d) in the wet season when the water table was higher. This seasonal difference indicates that, when saturated thickness is greater, the likelihood of intercepting more transmissive layers increases; such layers are likely to be bands of coarser (less clayey) material within the regolith. Specific yield estimations have a relatively wider range over several orders of magnitude (0.00001 to 0.32) and are more uncertain, because the estimates are more sensitive to uncertainties in well geometry (hand-dug wells are rarely cylindrical), in curve matching (occasionally only part of a curve was available for matching due to short test duration), and to the geology (the lowest value may represent a confined system created by a shallow low-permeability layer within the regolith). The mean specific yield of 0.09 (median: 0.08) is reasonable in comparison with literature values: a similar wide range was quoted by Jones [61] of 0.00001 to 0.1 for regolith in Central Africa and a textbook range for regolith of 0.15–0.3 was presented by Fetter [62]. A discussion on the pumping test results is presented in greater detail in Walker (2016). Estimates of well yield average 0.5 L/s though this increases to >1 L/s in the wet season, which provides optimism as 1 L/s is considered the minimum yield required to sustain small-scale irrigation [21].

4.6. Citizen Science Hydrometeorological Monitoring Programme

Groundwater levels rise almost to ground level in the wet season with little lag (1–2 days) in response following storm events suggesting significant and rapid recharge (Figure 4). Groundwater recession rates vary, and are steeper close to the head of the monitored sub-catchment where wells dry out in the dry season. Wells lower in the sub-catchment have groundwater available for longer and throughout the dry season when at the foot of hillslopes. The rivers respond rapidly to rainfall (in the wet season), indicating prevalence of surface runoff and/or fast interflow. River water levels reduce almost to zero in the dry season, and rise to 3 m or more during flood events.

Water balances were calculated on a monthly time step utilising citizen science rainfall and river stage data, which were converted to discharge following flow gauging and development of a rating curve, and PET calculated from NMA data (Table 1). The water balance was calculated by the equation: inputs (rainfall)—outputs (PET and discharge) = change in storage (ΔStorage). During the wet season, the high positive ΔStorage indicates that there is substantial water excess that is stored in the shallow aquifer, in soils, and as surface water on the inundated floodplain dambos. The subsurface storage augments river discharge during the dry season (i.e., when ΔStorage is negative). The storage values quoted are likely to be underestimated (ΔStorage is in reality larger than stated) as the water balances use potential rather than actual evapotranspiration (AET). Given the magnitude of ΔStorage increase in the wettest months (conservatively up to 181 mm), the thinness of the shallow aquifer (1–5 m below floodplains), and the quite low specific yield of the aquifer materials (0.09), there may not be the required storage volume available in the shallow aquifer (in addition to storage on the floodplain surface). Therefore, the magnitude of the positive ΔStorage values may be revealing additional losses from the system. These losses could be one or a combination of: (a) ET from phreatophyte vegetation or directly from open water at a greater rate than the grass reference PET rate (for shallow water bodies, FAO56 indicates 5–15% more than reference PET [55]); (b) lateral groundwater flow that bypasses the river gauge (refer to later stable isotope evidence), and; (c) seepage to deep fractured and scoriaceous layers (refer to later hydrochemical evidence). The high negative ΔStorage values during the dry season, which result in a negative annual balance for the Kilti watershed, are caused by the use of PET in the water balance calculation rather than by using AET. Moisture-limited conditions mean AET would be less than PET during the dry season, and therefore, the negative change in storage is expected to be less than what the calculation shows.

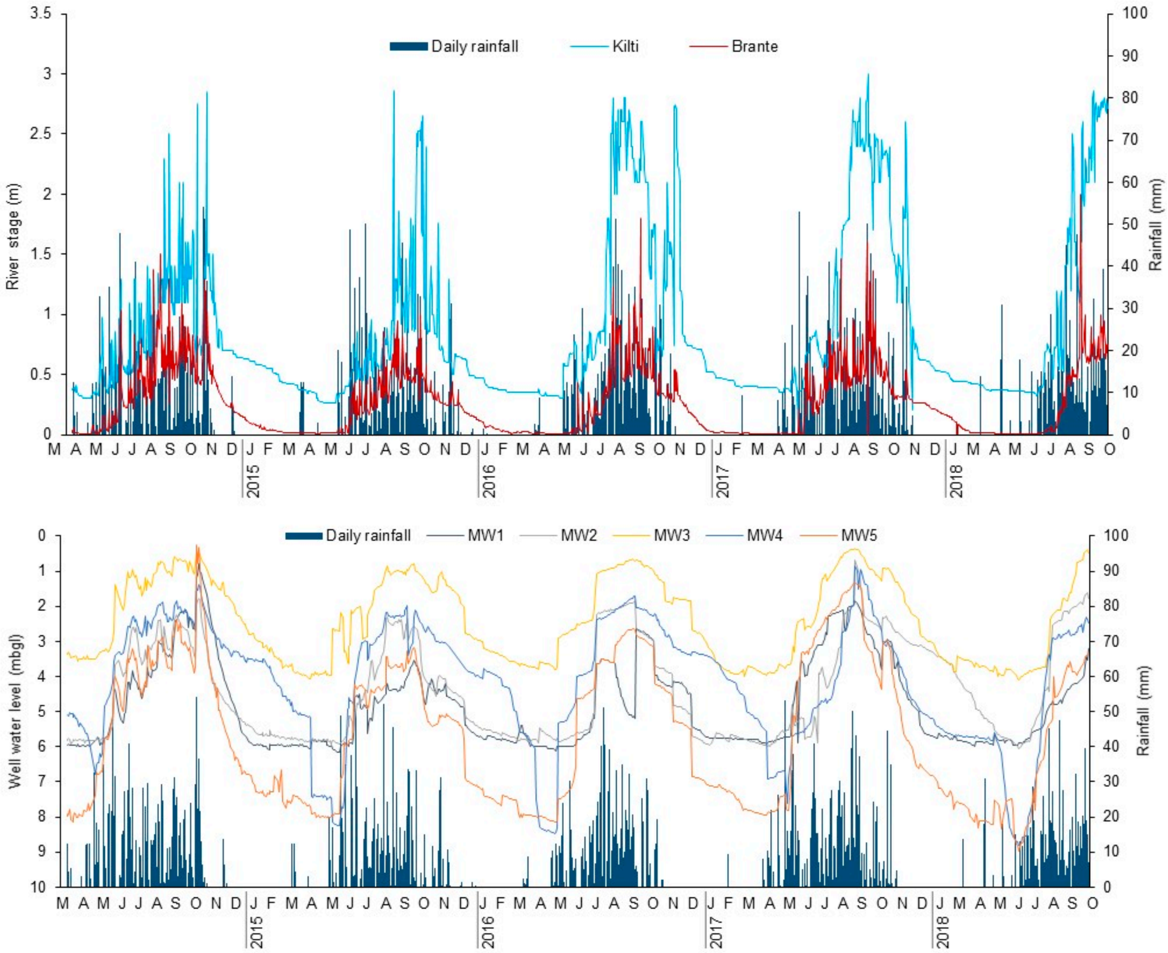

Figure 4. Time series from the citizen science hydrometeorological monitoring programme in Dangesheta *kebele* (Abadira *kebele* time series not shown). Top: river stage in the Kilti and Brante Rivers and rainfall. Bottom: groundwater levels in five wells (MW) and rainfall.

Table 1. Mean monthly water balance for 2014–2018 for the Brante (66 km^2) and Kilti (165 km^2) catchments; note that both use rainfall and potential evapotranspiration (PET) from the Dangila NMA weather station (see Figure 1 for catchment locations). ΔStorage is the change in total water storage in groundwater, soils, and surface water (i.e., inundated floodplains). All values provided as millimetre depth.

Brante	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Total**
Rainfall	0.0	6.3	28.9	58.3	197.7	219.3	294.5	340.0	198.0	145.3	22.8	0.8	1512.0
PET	119.8	114.0	126.2	124.3	105.6	98.2	89.9	86.5	94.4	101.5	108.0	111.3	1279.8
Discharge	0.3	0.0	0.0	0.1	6.0	15.5	47.4	72.6	50.3	30.0	7.7	2.0	231.9
ΔStorage	−120.1	−107.7	−97.3	−66.1	86.1	105.6	157.2	180.9	53.2	13.8	−92.9	−112.5	0.3
Kilti	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Total**
Rainfall	0.0	6.3	28.9	58.3	197.7	219.3	294.5	340.0	198.0	145.3	22.8	0.8	1512.0
PET	119.8	114.0	126.2	124.3	105.6	98.2	89.9	86.5	94.4	101.5	108.0	111.3	1279.8
Discharge	5.7	3.9	3.3	3.4	7.7	13.8	66.2	128.0	86.8	58.8	13.5	8.3	399.5
ΔStorage	−125.5	−111.5	−100.7	−69.4	84.4	107.3	138.4	125.5	16.7	−15.0	−98.7	−118.8	−167.4

4.7. Recharge Assessment

The different recharge assessment methods provided a wide range of recharge estimates from 45–815 mm/a (millimetres per annum) [40]. This wide range can be explained by differences in what the calculated "recharge" actually represents for particular methods and the spatial and temporal scales that the method considers. Significantly, for the development of the hydrogeological conceptual model, methods that measure *potential* recharge, i.e., unsaturated zone methods, gave much higher recharge estimates than methods measuring *actual* recharge, i.e., downward flowing water that reaches the water table and contributes to the groundwater reservoir. Clearly, there are losses to the infiltrated water before it reaches the water table; this loss is interflow followed by surface discharge, and such shallow springs are common at the study site. Methods that measure *minimum* recharge, i.e., baseflow separation methods that measure groundwater discharge to rivers, gave much lower recharge estimates than *actual* recharge methods. Therefore, additional losses must have occurred from the groundwater reservoir following recharge. These losses could be: upwards due to ET from the saturated zone, which would be expected given the very shallow wet season water table; laterally as groundwater flow that bypasses the gauge and/or; downwards as seepage to deep fractured and scoriaceous layers (see later discussions for evidence for and against the latter two losses). Importantly, the assessment revealed that recharge is high, the *actual* recharge estimate was 280–430 mm/a, and the shallow groundwater can be considered a renewable resource.

4.8. Hydrochemistry

Surface water and shallow groundwater belong to the calcium-bicarbonate type typical of recent recharge (Figure 5). Deep groundwater (samples from boreholes with depths >100 m) is of sodium-bicarbonate type indicative of higher mineralisation due to longer residence time and greater distance of flow. Low EC and ionic concentrations (Table 2) indicate that shallow groundwater residence time is low, suggesting that the resource could be vulnerable to drought. Shallow groundwater samples from the wet season are very similar in chemistry to surface water samples indicating a high degree of, and rapid, interconnectivity. This was expected in the wet season due to the observed very shallow water table.

Regarding the dry season shallow groundwater samples, 82% of samples had ionic balance calculations within ±10% (the acceptable range for waters with low concentrations of ions). From the subsequent wet season field visit, only 43.8% of samples were within ±10%. Additionally, duplicate samples showed an average discrepancy in measured concentrations of 16.6%. Therefore, the absolute concentrations are not presented with high confidence. However, the differences in water types are sufficiently evident that such possible inaccuracies in precision do not invalidate the usefulness of the data (see Supplementary Materials for further discussion on data quality assurance).

Table 2. Average values of measured hydrochemical parameters per water source and season.

	Sample Depth * (mbgl)	In-situ Measurement					Laboratory Analysis (mg/L)											Ionic Balance Error	VSMOW (‰)	
		Temperature (°C)	pH	EC (µS/cm)	222-Rn (Bq/m^3)	No. of Samples	Ca^{2+}	Mg^{2+}	Na^+	K^+	Fe^{2+}	Cl^-	F^-	SO_4^{2-}	NO_3^-	HCO_3^-	CO_3^{2-}		$\delta^{18}O$	δ^2H
Shallow groundwater (dry)	8.6	22.9	6.0	207	Nt	18	18.4	3.6	2.6	2.5	0.6	2.2	0.4	2.1	2.8	73.8	0	−2.0%	−1.88	−0.44
Shallow groundwater (wet)	5.8	22.9	5.7	173	7240	18	17.8	5.9	6.6	1.9	0	2.8	nt	5.6	5.9	50.8	nt	23.3%	5.37	0.31
Surface water (wet)	0	23.9	6.4	113	739	8	9.5	6.6	2.0	3.1	nt	2.1	nt	19.6	2.1	63.9	nt	−12.1%	17.6	1.09
Deep groundwater (wet)	140	22.4	8.8	325	ft	2	1.8	4.3	34.3	1.9	0	1.7	0.6	0.8	1.2	97.6	nt	7.2%	−2.50	−1.62
Rain water	na	nt	nt	nt	nt	3	nt	nt	nt	nt	nt	0.7	nt	1.4	0.9	nt	nt	na	34.1	3.74

* Sample depth = well/borehole depth. Values are uncertain as word-of-mouth measurements are included in the case of handpumps. Spring samples are given sample depths of zero explaining the lower average depth for "Shallow groundwater (wet)" compared to "Shallow groundwater (dry)" as a larger proportion of springs could be sampled. mbgl = metres below ground level, na = not applicable, nt = not tested, ft = failed test (due to equipment failure).

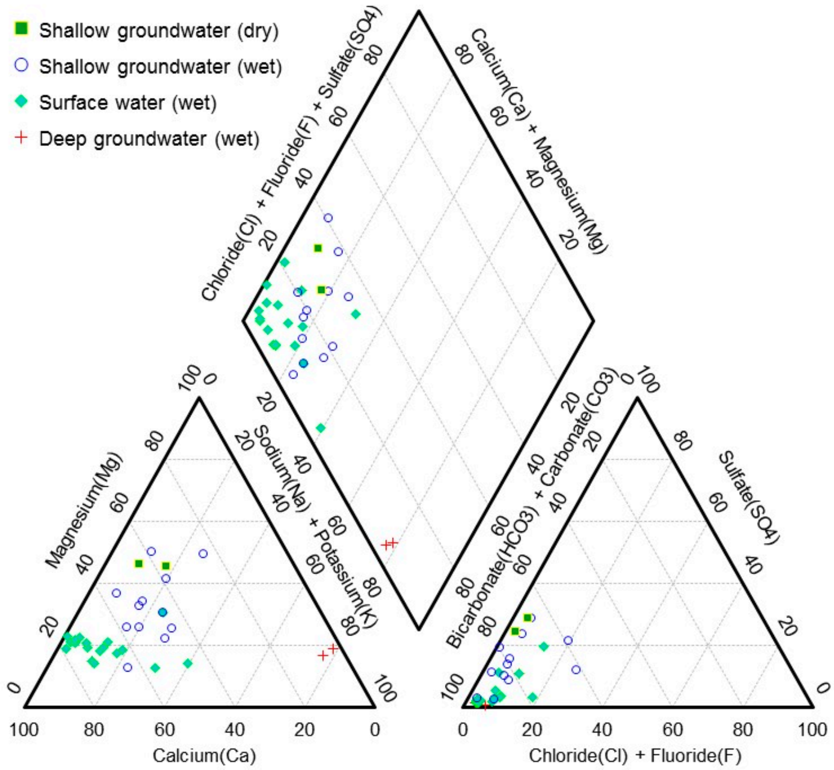

Figure 5. Piper plot of hydrochemistry by water source and season.

Figure 6 shows clear differences in stable isotope signatures between water sources and notably between shallow groundwater sampled in the dry season and from the wet season. A local evaporation line can be drawn through the wet season shallow groundwater and surface water values at odds with the dry season shallow groundwater results, which plot close to the local meteoric water line. The surface water samples are indicative of evaporation causing enrichment, which would be expected as rainfall collects in dambo wetlands before accumulating to form streams and rivers. The wet season shallow groundwater results are also enriched and similar to the surface water results indicating recently recharged water that infiltrated from wetlands. The slightly lower enrichment of the shallow groundwater than the surface water suggests mixing with diffusely recharged and thus less evaporated and enriched water. The dry season shallow groundwater results plot close to the local meteoric water line, suggesting diffuse recharge over a wider portion of the catchment, not only from the dambo wetlands. The deep groundwater was sampled during the wet season and plots away from other wet season groundwater samples, indicating little interconnectivity. The deep samples show the highest depletion meaning recharge could have occurred at distant mountainous areas. The rainwater samples show very high enrichment. The cause of this enrichment is suggested to be the urgency to sample rainwater during the few rainfall events to occur during the multiple field visits. This led to sampling of the early part of a storm when rain is isotopically enriched because heavier molecules condense first. The enrichment was not caused by evaporation, e.g., from a raingauge, because sampling was undertaken directly from falling rain during intense storms at night.

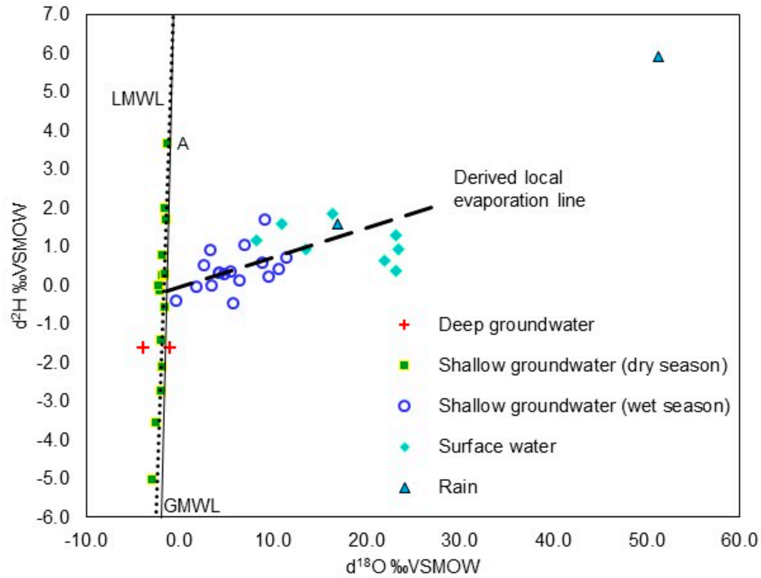

Figure 6. Stable isotope measurements by water source and season. Global Meteoric Water Line (GMWL) is shown as a solid line and Addis Ababa Local Meteoric Water Line (LMWL) is indicated as a dotted line [63]. Sample A is referred to in the text.

Wells reported by the community to have good year-round supply were often in unexpected locations. These wells were visited at the end of the dry season during the period of greatest water scarcity and contained water when many wells at the study site were dry. Often, such wells were located close to a surface water flow divide, and therefore, the wells' seemingly had a small up-gradient catchment area. Such apparently small recharge zones should not be conducive to the good year-round supply reported by the well owners. However, it was revealed that the recharge zone was actually much larger and extended beyond the surface water flow divide. Groundwater samples from such wells often showed greater stable isotope enrichment and higher ionic concentrations than what would be expected from their topographic position close to a flow divide where the flow path and groundwater residence time were expected to be short. For example, sample A in Figure 6 shows isotope enrichment and was sampled from location 1 in Figure 7a, around 300 m downslope of the flow divide. Commonly, across the flow divide from such perennial wells, e.g., the dotted line 2 in Figure 7a, there was a dambo. The higher enrichment (through evaporation when inundated) and higher concentrations (due to the longer residence time) suggest the sampled water originated in the dambo that provides continuous groundwater supply through the dry season with groundwater flow paths contradicting surface water flow paths. Location 3 in Figure 7a is such a dambo with a surface water outlet to the northeast (and to the south as an example of a dambo that cuts across watersheds referred to in the dambos section) as shown by the arrow in Figure 7a, though with a dry season groundwater gradient towards the southeast.

Figure 7. (**a**) Map showing seasonally inundated floodplain dambos with surface water flow directions indicated with thin arrows and shallow groundwater flow indicated by the thick arrow. The dotted line represents the surface flow divide. Locations 1–4 are referred to in the text. The northwest-southeast dashed line is the location of the cross-section in Figure 9. (**b**) Photograph from the 2015 dry season of the perennial well with a rope-and-washer pump at location 1. (**c**) Photograph of a saturated dambo at the end of the 2015 wet season close to location 3.

The deep and shallow groundwater samples plotted in different locations on the piper plot and stable isotope plot (Figures 5 and 6), and had different hydrochemical parameters as shown in Table 2, all of which evidence is not suggestive of mixing between the shallow and deep groundwaters; they belong to different water types. Radon-222 evidence supports this hypothesis: measurements of surface water close to deep abstracting boreholes were taken to assess if surface water and shallow groundwater were being drawndown into the deeper aquifer due to abstraction. If there was good connectivity between the shallow and deep groundwater, it could be expected that ^{222}Rn concentrations would be lower in the vicinity of the abstracting boreholes as groundwater discharge to surface water would be prevented (shallow groundwater flow would be downwards rather than upwards or laterally into the river). However, field measurements showed no reduction in ^{222}Rn close to abstracting boreholes (Figure 8a). ^{222}Rn concentrations increased in a downstream direction along floodplain dambos indicating that they are areas of groundwater discharge from the shallow regolith aquifer, whereas the narrower valleys with basalt riverbeds had lower ^{222}Rn concentrations indicating they are not discharge areas. Figure 8b shows the highest ^{222}Rn concentrations at a spring and a shallow well at the head of a sub-catchment. Concentrations then decrease along the flow path, as would be expected as time elapses since the water was discharged from groundwater, until floodplain dambos are reached and concentrations increase. However, it should be noted that the faster, more turbulent flow through rocky reaches may have a degassing effect on the river water thus reducing ^{222}Rn concentrations [53]. All ^{222}Rn testing was conducted during the wet season and this pattern of recharge and discharge zones reverses late in the dry season (see the hydrology section) when floodplain dambo streams are often dry and flow only occurs in the narrow valleys with basalt riverbeds.

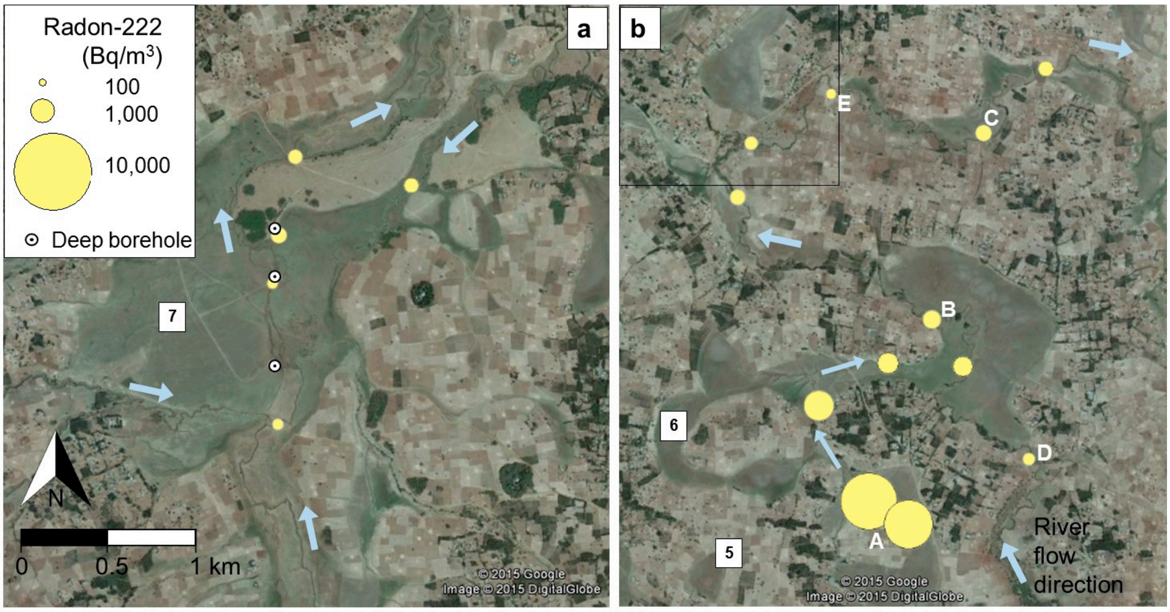

Figure 8. (**a**) Radon-222 measurement locations and results showing evaluation of impact of deep (150 and 192 m) abstracting boreholes on surface water and shallow groundwater; (**b**) Radon-222 measurement locations and results showing ^{222}Rn concentration variation with distance along surface flow path from source (location A). Note the elevated concentrations in broad dambo floodplains (locations B and C) in comparison to narrow valley samples (locations D and E). Locations 5–7 are referred to in the text. The black box shows the location in Figure 7a (which extends to the north).

Ethiopia is known for having problems with fluorosis caused by excess fluoride in groundwater (though the issue is typically confined to the Rift Valley and deep boreholes [64]); here, the maximum measured F^- level was 0.8 mg/L, below the World Health Organisation (WHO) [65] recommended maximum of 1.5 mg/L. Nitrate is a potential contaminant due to the proximity of wells to pit latrines but the maximum measured NO_3^- was 11.5 mg/L, below the WHO limit of 50 mg/L. The WHO does not give a guideline value for iron concentration in drinking water though four samples were above the 0.3 mg/L at which water discolours and staining can occur. Sodium adsorption ratios (SARs) were very low: <1.0 for all samples except the deep groundwater, which had SAR of ~3.0. An SAR of >3.0 is considered potentially problematic for irrigation water [66]. Considering only hydrochemistry and not microbial content, the analyses indicate that all the groundwater tested is suitable for both irrigation and potable use. The full set of hydrochemistry results and further discussion is provided in Supplementary Materials.

4.9. Hydrogeological Conceptual Model

The shallow aquifer comprises regolith above low-permeability basalt. While it is likely that fractures in the upper layers of the basalt are influential to the hydrogeological regime [61,67], fissure flow is not expected as fractures are likely to be filled with weathered material with similar properties to those of the overlying regolith. The precise depth and degree of fracturing of the solid geology is very difficult to estimate without subsurface investigations (drilling) or geophysics.

Near the end of the dry season in March/April, the thin aquifer below floodplains has a very low saturated thickness (<0.5 m). Where the aquifer is thicker at the foot of slopes, saturated thickness is greater though higher on slopes saturated thickness again reduces.

There is little evidence of connectivity between the shallow regolith aquifer and deeper water-bearing fractured or scoriaceous layers within the underlying basalt. Hydrochemistry and stable isotope analyses indicate different shallow and deep groundwater types while variation in radon-222 concentrations was not suggestive of surface water or shallow groundwater losses to a deeper aquifer. However, water balance calculations and recharge estimates from methods calculating actual and minimum recharge indicate there are losses from the shallow groundwater aquifer in addition to those from discharge into springs and rivers. These losses are likely to include ET from the saturated zone where water tables are shallow, lateral groundwater flows that bypass the gauge, and may involve seepage to deep fractured and scoriaceous layers, though there is no hydrochemical evidence of the latter. Dambo formation due to heightened leaching and subsidence could suggest presence of fracturing [58] and therefore possible connection to deep groundwater. However, this does not necessarily contradict our hydrochemical evidence, as the fracturing can promote shallow groundwater flow laterally which then emerges as springs downstream of the river gauges. This situation is described in numerous modelling studies in the region and is often suggested to represent unmeasured outflows in order to satisfy catchment water balances (e.g., [68–70]).

The shallow aquifer and surface water are in connection, particularly during the wet season when large areas are inundated. Wet season hydrochemistry and stable isotope evidence indicate that recharge is rapid and groundwater residence time is low. However, the clay content of the floodplain dambos means that rains at the onset of the wet season may form a perched saturated layer above a shallow low hydraulic conductivity layer. This exacerbates flooding as infiltration is restricted, and rainfall and shallow spring discharge at dambo edges feed into ponded surface water which passes slowly overland through thick grasses and sedge into river systems. The constricted dambo outlets (Figures 7a and 8) restrict floodplain surface water discharge, which contributes to the formation of wetlands. Infiltration through coarser lenses and slowly through the low hydraulic conductivity layer, in addition to lateral groundwater flow, ultimately create a single connected surface water and groundwater body. Future research in the region to fully understand the significance of dambos for recharge and runoff generation is recommended.

Evidence indicates that shallow groundwater flows laterally in directions not necessarily coincident with surface water flow paths, as proposed in published literature on regolith hydrogeology [61,67]. Numerous surveyed wells were observed to have good perennial supplies despite appearing to be close to watershed boundaries with consequently small recharge zones. Further investigation often revealed up-gradient floodplain dambos that lay across surface watershed divides, where the underlying bedrock topography promotes groundwater flow in the direction of the wells (Figure 9). Stable isotope results of groundwater from wells in such locations showed evaporation signatures consistent with infiltration below a floodplain wetland. The conceptual model is an example of local groundwater flow systems at odds with regional flow; a situation first described by Toth [71], whose flow system diagrams are found in most hydrogeology textbooks.

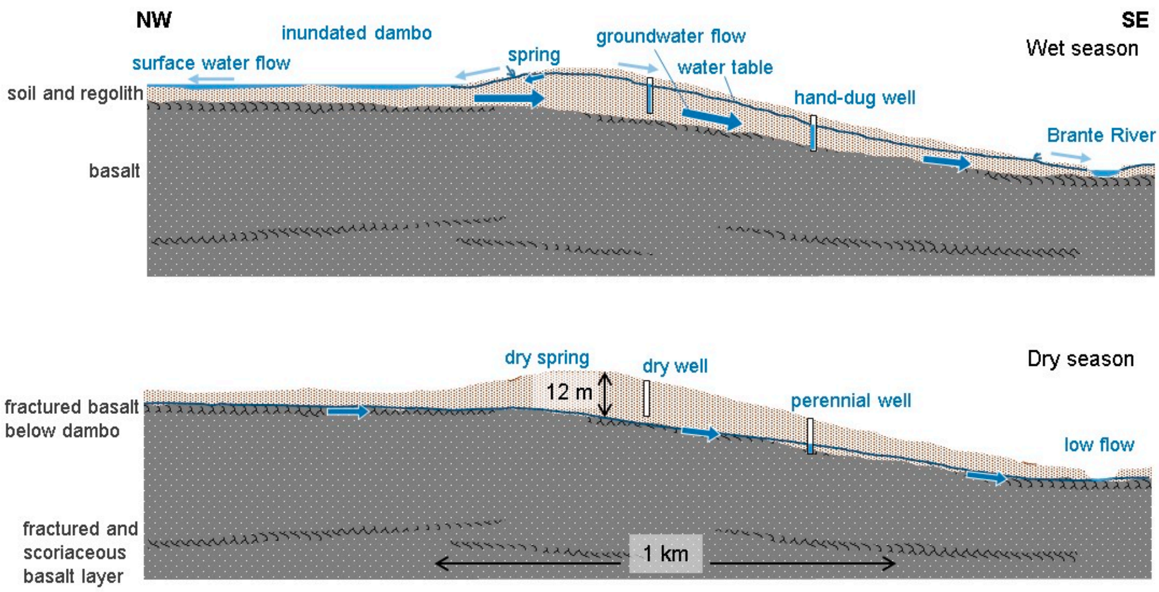

Figure 9. Schematic cross-sections showing the conceptual model during the wet and dry seasons. The cross-section represents a common profile at the study site, e.g., the NW-SE line shown in Figure 7a. Note the very shallow groundwater flow (and unsaturated zone flow) in contrary directions to the dominant regolith aquifer groundwater flow during the wet season and groundwater flow contrary to surface water flow at the up-gradient dambo.

4.10. Transferability of the Research

Many of the concepts in the conceptual model should be transferable across a wider area than only the vicinity of the study site. Weathered regolith above Cenozoic volcanics underlies the region: around 40% of Ethiopia is underlain by Cenozoic volcanic rocks [72] and similar geology can be found all along the East African Rift from Eritrea to Malawi and in unconnected areas such as Western Cameroon/Eastern Nigeria and Southwest Sudan. The study site is within the moist and extensive Ethiopian Highlands: ~50% of Ethiopia receives rainfall of >1000 mm/a, in comparison to the country-wide average of 817 mm/a [73]. The study site is currently reliant on rainfed agriculture: 90–95% of farmed land in sub-Saharan Africa is rainfed [74]. The Dangila conceptual model can be used as a reference for concepts developed from detailed hydrogeological investigations elsewhere.

The methodology of this research is generally transferable. The framework for conceptual model development by Brassington and Younger [17] is tried and tested in this study for a data-scarce region. Research has shown that local communities can collect high-quality hydrometeorological monitoring data for assessing resource seasonality and availability [38]. Multi-method recharge assessments are recommended for assessing the renewability of the shallow groundwater resource in addition to providing insights into the conceptual model [40]. Applying hydrochemistry, stable isotope, and radon-222 analyses in combination greatly aids conceptual model development. Surveys of wells (measuring the depth and groundwater level and determining the seasonality), including conversations with local stakeholders, are invaluable for assessment of aquifer geometry, groundwater recession rates, and areas of highest/lowest potential for increased abstraction.

5. Conclusions

A combination of field investigations including geological, hydrological and water point surveys, hydrochemistry, stable isotope and radon-222 analysis, and pumping tests, in addition to citizen science hydrometeorological monitoring and a multi-method recharge assessment, have enabled the development of a hydrogeological conceptual model.

A shallow thin regolith aquifer sits above largely impermeable basalt with little connection between the shallow groundwater and deep groundwater found in fractured and scoriaceous zones. Common seasonally inundated floodplain wetlands are akin to such features known as dambos in Southern Africa. These dambos can be considered groundwater stores often providing a water source for down-gradient shallow wells during the dry season. Directions of groundwater flow from these dambos sometimes contradict surface water flow and interflow directions. The variations in geology are sufficiently subtle, particularly concerning the regolith which forms the shallow groundwater aquifer, to be less of a control over the hydrogeology than topographic position.

While hydraulic conductivity (and consequently well yield) and specific yield of the shallow aquifer are quite low, they are not too low for small-scale irrigation, especially if abstraction commenced at the immediate cessation of the wet season when aquifer saturated thickness and well yield are highest. Hydrochemical analysis indicated that the shallow groundwater is suitable for irrigation.

The limitations of this study result from the low-density hydrometeorological monitoring network and sparse geological outcrops at the study site, meaning interpolation of results is necessary across broad areas. While the citizen science programme is expanding, greater confidence in the geology of the study site could only be gained through geophysical investigation complemented with borehole logs. Additionally recommended is broader investigation into the role of dambos in Ethiopia in augmenting dry season baseflow and shallow groundwater levels.

This study provides the conceptual basis for development of quantitative hydrogeological simulation models, which can help to interpret in more detail the spatial and temporal variability of shallow groundwater availability, and its susceptibility to climatic, land use, and abstraction pressures, to support integrated land and water management.

Supplementary Materials: The following are available online at http://www.mdpi.com/2306-5338/6/2/43/s1, Table S1: Results of in-situ testing and laboratory analysis from the first field visit in March/April 2015, Table S2: Results of in-situ testing and laboratory analysis from the second field visit in October/November 2015, Table S3: Comparison of in-situ testing results from February/March 2014, March/April 2015, and October/November 2015, Figure S1: Photographs showing radon-222 testing, in addition to further description and discussion of the hydrochemistry field investigations.

Author Contributions: Conceptualization, D.W., G.P., J.G., and A.T.H.; methodology, D.W., G.P., J.G., and A.T.H.; software, D.W.; validation, D.W.; formal analysis, D.W.; investigation, D.W.; resources, D.W., G.P., J.G., and A.T.H.; data curation, D.W.; writing of original draft preparation, D.W.; writing of review and editing, D.W., G.P., J.G., and A.T.H.; visualization, D.W.; supervision, G.P. and J.G.; project administration, D.W., G.P., J.G., and A.T.H.; funding acquisition, G.P. and J.G.

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Conflicts of Interest: The authors declare no conflicts of interest.

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