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ORIGINAL ARTICLE

Initial observations of water quality indicators in the unconfined shallow aquifer in Dili City, Timor-Leste: suggestions for its management

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Abstract
The management of groundwater quality is a critical issue in developing nations where sanitation and drinking water targets are commonly addressed by facilitating access to groundwater, which is then managed as a common-pool resource. We investigate the quality of the shallow unconfined groundwater in Dili's alluvial fan system, which 50% of Dili's rapidly growing population use for all their water requirements. Using the basic chemical and microbiological analyses that are locally available (sulfate, total hardness, fluoride, manganese, iron, ammonia, nitrite, nitrate, total coliform and *E. coli*) we show that the shallow wells commonly contain enhanced concentrations of dissolved solids and microbiological contaminants (total coliform and *E. coli*), relative to deeper wells. Cool, shallow wells are worse than warm equivalents. Elevated nitrate and nitrite pollution in the embassy district are tentatively attributed to affluence factors, such as lawn cultivation and water filtration equipment. Microbiological contamination, and associated manganese contamination of groundwater, mimic population patterns, but are concentrated in the finer grained sediments of the small fans and low-slope interdistributary areas. We suggest that rapid development and successful implementation of appropriate sanitation policy in Dili (and elsewhere) is required to address the problematic features of the shallow groundwater system. Success will be predicated on (1) the establishment of baseline data, and (2) development of a systems-thinking approach to holistic water resource management.

Keywords Unconfined aquifer · Coliform contamination · Developing city · Groundwater quality · Dili · Timor-Leste

Introduction

The management of natural systems has been transformed by recognition of the ways in which human activities impact on those systems, and the resultant conflicts that emerge (Hipel et al. 2008). Nevertheless, in many (particularly developing) countries, critical natural systems such as groundwater continue to be managed, at least partly, as a common-pool resource, where beneficiaries of the resource commonly lack information about how their decisions and activities impact on the decisions, plans and benefits of other beneficiaries (Madani and Dinar 2012). Rapid development of appropriate water, sanitation and hygiene (WASH) policy, and public education about that policy in the context of a common-pool resource, is therefore, of particular concern for groundwater quality management in developing countries; however, the successful development and implementation of such policy is predicated on (1) the establishment of baseline data (Back et al. 2018), and (2) development of a complete understanding of the physical, climatic, socio-political, economic, and cultural factors that frame and underpin the value of the groundwater system (e.g., Barnaby 2009; Fowler et al. 2003; Gill et al. 2017; Jennaway 2008). Only with this knowledge in hand can sustainable development of the groundwater system proceed effectively under an essentially systems-thinking approach (e.g., Hipel et al. 2008) to holistic water resource management.

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Timor-Leste is a young nation located within eastern Indonesia, 200 km north of Australia (Fig. 1). The capital city, Dili, is located on a small alluvial fan on the north side of the island (Boger et al. 2013). Dili's urban population has expanded rapidly since Timor-Leste's independence at the turn of the century, growing by 15% between the 2010 and 2015 census

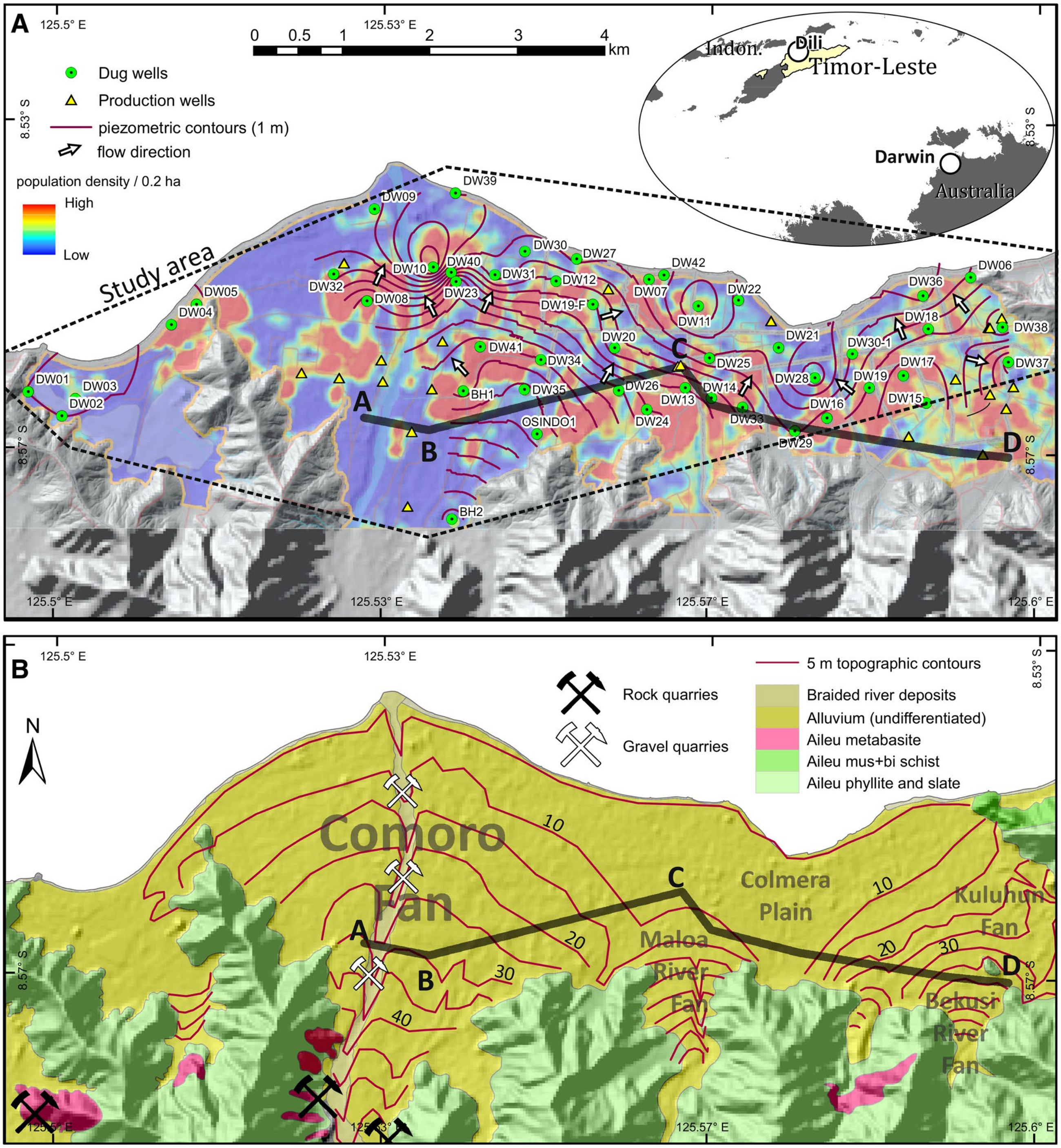

Fig. 1 Population density, hydrogeology, geology and geomorphology of the Dili area, with location map inset. **a** Piezometric contours for the unconfined aquifer, based on preliminary local interpolation of groundwater levels, and overlaid on a relative population density map. The distribution of dug wells closely reflects the population distribution patterns. **b** Geomorphology of the Dili Plain. Simplified contours highlight the coalescence of the prominent Comoro River Fan with the smaller Maloa River, Bekusi River and Kuluhun River fans in eastern Dili, resulting in development of several prominent, low-gradient interfan areas, like the Colmera Plain. Line ABCD shows trace of schematic cross section in Fig. 2a

to presently exceed 220,000; however, the development of Dili's water and sanitation infrastructure has lagged considerably behind its population growth. A report released in 2014 by WASH stakeholders in Timor-Leste indicated that 93% of the urban population used 'improved' water supply, although nearly 50% of these used non-piped sources (tubewells, boreholes and protected springs) (Timor-Leste WASH Stakeholders 2014). The same document reported that most urban toilets are pour-flush, but that less than 20% of households had ever emptied pits or septic tanks, which are, therefore, presumably leaking waste into the shallow aquifer. The Timor-Leste WASH Stakeholders (2014) report emphasized the need for regulatory and governance reform within the urban water sector, including improving the quality of service provision by *implementation of transparent testing procedures*. Piped water is extracted from a small number of deep bores across the Dili Plains, which access the deep confined levels of the aquifer system; however, many of the wells and boreholes that provide a large proportion of the city's drinking water access a shallow unconfined aquifer. The spatial and temporal scales and magnitudes of interaction of WASH and groundwater systems are well studied elsewhere (Graham and Polizzotto 2013; Ravenscroft et al. 2017) but, along with the extent of chemical contamination, have not been previously documented for Dili's groundwater system.

The logical starting point for governance and service quality improvements is to establish a water quality baseline for Dili, while evaluating how the city's population distribution and growth has impacted the quality of the largely common-pool groundwater resource that is directly accessed by nearly 50% of its population. In this paper, we present a preliminary analysis of the quality of groundwater in the Dili unconfined aquifer. We use a combination of geographic, physico-chemical and microbiological parameters, along with population density data, to investigate the social and geological controls on water quality in the shallow groundwater. Chemical parameters are selected based on limited locally available laboratory facilities, an approach that we consider appropriate to allow continued local monitoring from our baseline. Our analyses provide a snapshot of the factors affecting water quality in this small, but developing city. We briefly discuss how a systems-thinking approach might incorporate an understanding of social and natural systems in the management of the shallow groundwater resource.

Aquifer setting

Geological, geomorphic and hydrologic setting

Dili's hydrogeology is strongly influenced by its rangefront geological setting, which gives rise to two main aquifer types; the hydrogeology of the high topography south of Dili is controlled by a fracture system (localised aquifer of Wallace et al. 2012) within the slates, phyllites, mica schists and occasional meta-basalts of the Aileu metamorphic complex (Berry and Grady 1981, IPG 2014). The study area for this paper abuts the rangefront and consists of a potentially high-yield, intergranular aquifer, hereafter referred to simply as 'the Dili aquifer system', developed in the unconsolidated sediments underlying the alluvial plain on which Dili is built (the Dili Plain; Figs. 1, 2) (IPG 2014; Pinto et al. 2017; Wallace et al. 2012).

The Dili Plain is the surface of a composite, northward-thickening, Late Quaternary fan delta that progrades into the Wetar Strait. The internal structure of the Dili aquifer system will reflect its origin as a coarse-grained system of overlapping deltas; although its subsurface architecture is not well known, it is likely to conform with typical models for a Gilbert style fan delta, similar to uplifted equivalents observed further east along the north coast of Timor (Mills 2011) (e.g., Fig. 2c, d). Geotechnical drilling has encountered buried coral reefs at several meters depth that are consistent with Timorese fan deltas and probably compartmentalize groundwater flow.

The uppermost gravels of the Dili Plain host the Dili Unconfined Aquifer (hereafter 'the unconfined aquifer'), which provides drinking water for those ~50% of people in Dili City who cannot access the reticulated water system. The study area, which encompasses the entire city of Dili and its immediate surrounds, is small, extending only ~4.5 km N–S and ~12 km E–W at its maximum extents. The most prominent geomorphic feature of the plain is the Comoro River Fan (Fig. 1b). The Comoro River bed is incised ~10 m below the surface of the fan near the fan head. The Comoro River Fan is bordered to the east by a series of overlapping, smaller fans (The Maloa River, Bekusi River and Kuluhun fans). The intersections of individual fans form low-gradient areas, the most prominent of which is the Colmera Plain, a swampy area between the two eastern and two western fans. The Colmera Plain, which hosts Dili's central business district, reaches no more than 10 m elevation where it meets the rangefront, ~1.3 km inshore. Floods in Dili in 2010 were concentrated in the Colmera region, where they were exacerbated by poor and impeded drainage capacity (Santos Almeida et al. 2015).

The westernmost element of the study area, the Tasi-Tolu catchment, is completely separated from the remainder of the Dili Plain by a spur of schist and metamorphosed basalt bedrock (Fig. 1) and is thus probably hydrologically independent.

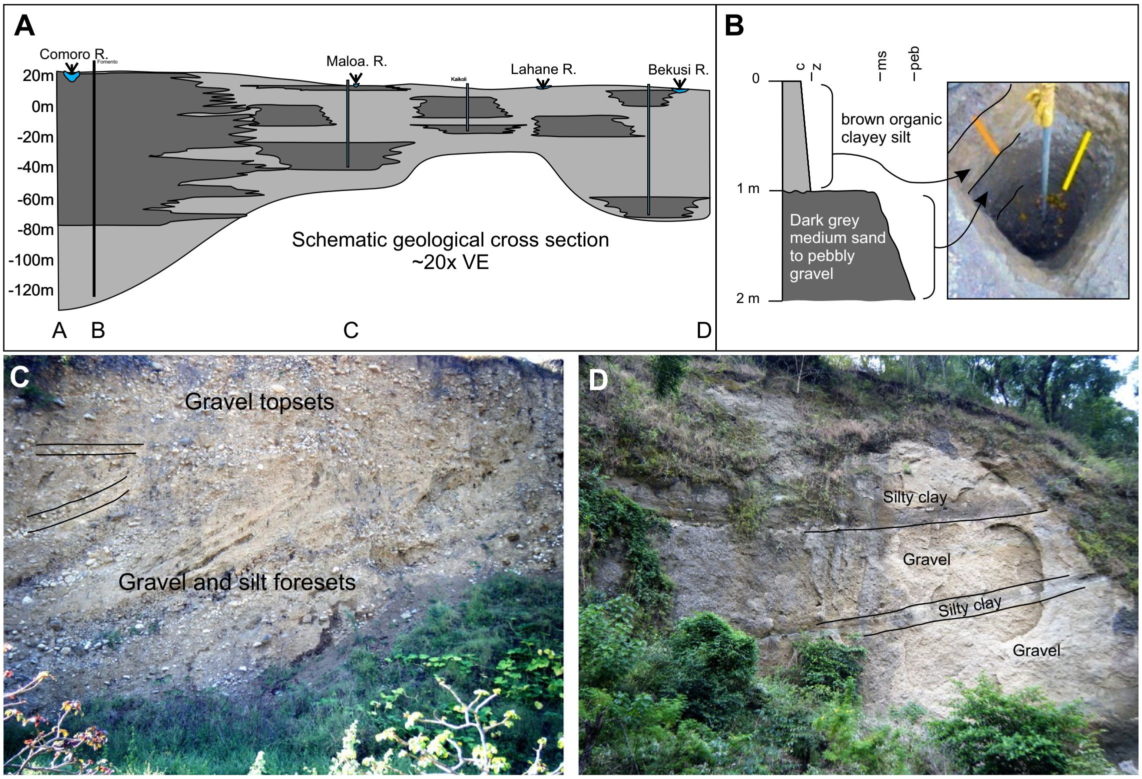

Fig. 2 Sedimentary context of the Dili aquifer system. **a** Schematic, approximately E–W cross section across the Dili aquifer system (see location on Fig. 1), showing the variable gravel thickness (dark) and fine-grained facies (light) at individual logged boreholes. **b** 2 m deep logged pit, showing general grain size relationships in surficial fan sediments. For pit location see DW10 on Fig. 1a. **c** A Gilbert-type fan delta, with gravel topsets and gravel/sand forests, just east of Baucau. **d** A typical deltaic sequence with gravel distributary channels intercalated with muddy delta front deposits

Climate and precipitation

The Dili aquifer is fed by precipitation in Dili and in the mountains south of Dili. Data provided by Timor-Leste's National Directorate of Meteorology and Geophysics (DNMG) indicates that Dili recorded an average annual temperature of 31.75 °C and an average annual rainfall of 1370 mm/year over the 3 years period 2014–2016. The estimated maximum 24-h precipitation for Dili is 193 mm and 230 mm for the 50 and 250 year return period, respectively (Santos Almeida et al. 2015). Most of the rain falls during a wet season that extends from November until June, although Timor's rainfall patterns are very sensitive to the El Nino Southern Oscillation (Aldrian and Dwi Susanto 2003), and La Nina years such as 2010 may have little dry season at all. The high elevation catchment of the Comoro River receives at least 50% higher rainfall than the fan surface itself; Pinto et al. (2017) report ~ 1800 mm/year in the head of the catchment, but this is based on interpolation of out-of-catchment gauges. Up to 3500 mm/year has been estimated on the divide by the Tropical Rainfall Measuring Mission (Christian et al. 1998); during the dry season much of the river flow from mountain precipitation infiltrates either the localised bedrock aquifer, or infiltrates at the head of the fan, so that the river remains largely dry as it crosses the fan. During the wet season, rivers may flood the Dili Plain as increased runoff exceeds infiltration capacity, sediment is mobilized in the mountains, and channels become choked as high volumes of sediment are deposited and stored at the rangefront slope break, leading to aggradation and avulsion-tendency at the rangefront.

Socio-economic context of water resources

Socio-economic factors affect the ongoing sustainability of the Dili aquifer and might be expected to manifest in the results of the present study (Fig. 3). Municipal water is extracted from deep bores whereas the unconfined aquifer exists primarily as a common-pool resource, with few bounds on competition between users. Dili is densely, but unevenly populated (Fig. 1a). The dense, increasingly sealed road network that serves this population resists infiltration and provides vehicular sources of pollution across the recharge zone. Many Dili residents access the unconfined aquifer directly through dug wells and bores. The lack of municipal sanitation creates competition between waste

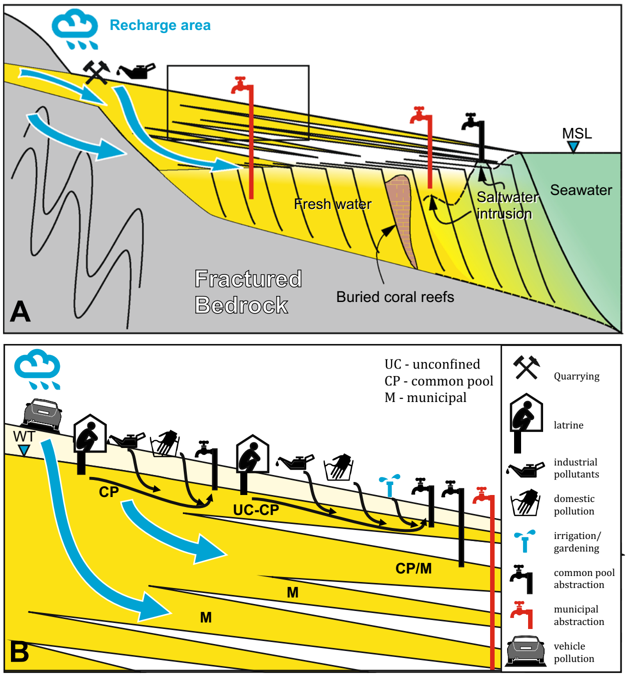

Fig. 3 Schematic cross section showing Dili aquifer. Yellow shows freshwater lenses (gravels) and white shows interbedded fine sediments that retard or occlude vertical groundwater flow. **a** Key issues for management of this resource at a large scale include (1) industrial contamination of the recharge zone; (2) the potential for saltwater intrusion caused by over exploitation close to the coastline; (3) lack of understanding of the physical structure, which is shown here based only on interpretation of the probable depositional setting. **b** The lower image shows a schematic of the many activities of humans that have been shown to compromise the quality and quantity of the water resource

disposal and water abstraction, especially where wells are sited close to sanitation facilities or groundwater is close to the surface in drained swamps (Fig. 4). Poor stream management strategies on the fan surface, such as poorly maintained, narrow, rubbish blocked and/or vegetated/cultivated drainage channels (Fig. 4), contribute to flooding (Santos Almeida et al. 2015) that may impact on the quality of aquifer recharge by mobilizing pollutants from the ground surface.

Quarrying in/near the Comoro River (Fig. 1b) mitigates any tendency for the river to aggrade at the range front, effectively reducing flood risk on the Comoro Fan, but also potentially reducing recharge of near-surface aquifers. Heavy machinery disturbs the river bed, mobilizing fines that are transported as dust out of the river bed. The increased porosity and permeability of the river bed may facilitate recharge of deeper aquifers, but the unregulated use of leaky hydraulic equipment and vehicle engines provides multiple point sources of contamination that are washed into the aquifer during the wet season. Most of Dili's municipal waste is dumped in an open site just west of the study area, where it is separated from the Dili aquifer system by a bedrock sill.

Materials and methods

In November 2016, shortly after the onset of the rainy season, we visited 33 sampling points comprising both dug wells and boreholes. Groundwater level was measured using a Solinst Water level meter and well coordinates recorded with a Garmin GPS CX76. At each sampling point, we collected samples in 500 ml sterile

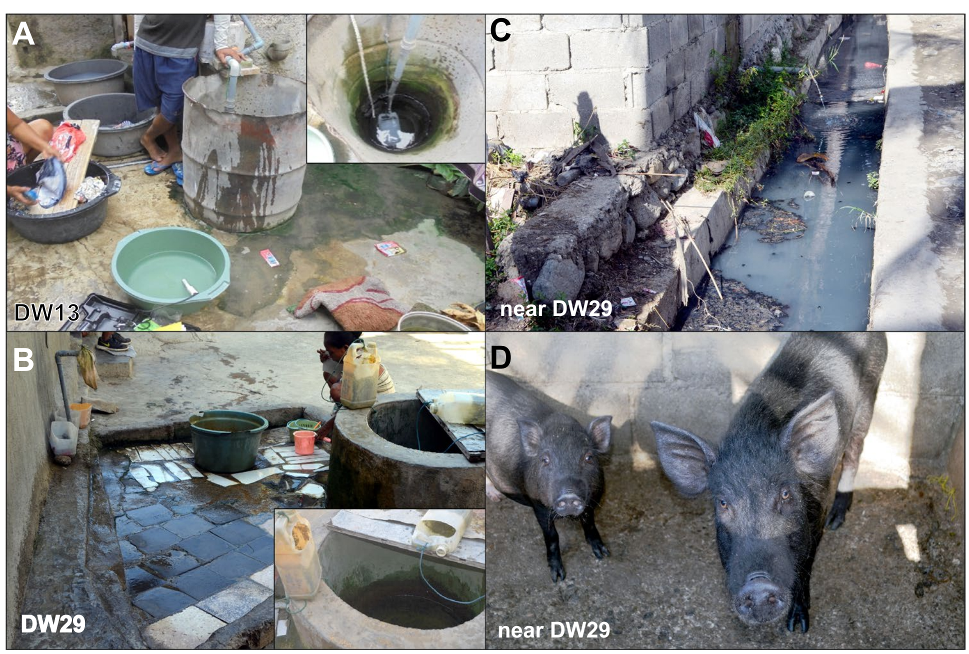

Fig. 4 Social context of wells. **a** Well DW13, showing the small separation between the well and the toilet, against which the man is leaning. Note the standing water and un-segregated washing activities around the well. **b** Well DW29, again showing a washing pit adjacent to the well. Inset shows shallow depth to water in well, which is visibly bluish grey. In this case, the green bucket covers an outlet that leads to the open drain shown in **c**. The water level in the drain and well are identical (~15 cm below the ground surface) in this picture taken at the start of the dry season (31 May 18), but the groundwater drops to ~0.45–0.75 m in this area by the end of the dry season. **d** Livestock a few meters from **c**

plastic bottles for chemical and microbiological analysis. Pumped well and borehole samples were collected after pumping for 5 to 10 min. Standing water was manually sampled only where dug wells were not fitted with pumps. All samples were refrigerated immediately using ice boxes, and transported to the laboratory within 4 h of collection.

The physical properties of groundwater samples (pH; electrical conductivity—EC; total dissolved solids—TDS; temperature) were measured *during sample collection* using a digital Hanna pH meter (HI9813-5). Our samples were generally warmer than the conventional 25 °C reference temperature for the conductivity of natural waters, so we applied the USGS-recommended correction (Radtke et al. 2005) based on Eq. (1), which is consistent with ISO 7888 (1985):

$$C_{25} = \frac{C_{m}}{1 + 0.02(t_{m} - 25)}, \quad (1)$$

where C_{25} = corrected conductivity value adjusted to 25 °C; C_m = actual conductivity measured before correction; and t_m = water temperature at time of C_m measurement.

The concentrations of ammonia, nitrite, nitrate, iron, manganese, fluoride, sulfate, total hardness, calcium, and magnesium were analysed at the Laboratório Nacional dá Saúde, Timor-Leste, using a Hach DR/2010 Spectrophotometer. These chemical parameters were selected based on the limited analytical facilities available in Dili.

Total coliform and *E. coli* were counted using the multiple tube fermentation technique, following the American Public Health Association's standard procedure (APHA 2006) (presumptive, confirmed, and completed phases), and leading to an estimate of the most probable number (MPN) of organisms.

All piezometric, physical, chemical and microbiological data were interpolated by kriging and contoured using Golden Software's Surfer mapping programme. GeoTiff files were exported to ArcGIS and displayed alongside relevant datasets including administrative boundaries, hydrological and hydrogeological features (rivers, wells, boreholes, etc.) and geology. The direction of unconfined groundwater flow was interpreted to be perpendicular to the piezometric contours obtained from variations in the static water levels across the study area. The point dataset is available as a supplementary online file.

Population density was calculated from a 2015 census dataset of residential dwellings. Density was calculated within a radius of 50 m (area ~ 0.2 ha) around a given dwelling, using the ArcGIS point density tool, and attributed to a 30-m cell. Population density is displayed with a two-standard-deviation stretch applied.

Results and interpretation

Most of the wells that are used by the community target the unconfined aquifer. Nearly 70% of the 47 wells that we used for contouring were less than 4 m deep. Our contouring of groundwater levels implies that the shallow unconfined groundwater flows mostly northwards, except in the Aimutin area where it flows more westerly toward the deeply incised Comoro river.

The in situ groundwater temperature in the Dili aquifer system ranged from 26 to 39 °C, with a modal temperature of 29 °C. Shallow wells are generally the warmest (Fig. 5), suggesting that high water temperatures occur mostly in the unconfined aquifer and reflect elevated atmospheric temperatures.

Most water was slightly alkaline, and only a few wells were slightly acidic (Fig. 5a). TDS is predominantly an indicator of the salinity, and therefore, palatability of drinking water; The TDS of the study wells varied from 105 to 2500 mg/L (Fig. 5b), with EC ranging from 288 µS/cm to 6.412 mS/cm, respectively. Approximately 57% of wells returned TDS below 600 mg/L and 90% (40 of 47) were below 1000 mg/L, the typical limit of palatability (Griffioen 2004; WHO 2011a). No wells deeper than 4 m exceeded TDS values of 600 mg/L (Fig. 5b).

Dissolved solids, sulfate and fluoride

Elevated TDS values occur in several patches across the rest of the city, notably in coastal areas (Fig. 6). These indicate potential high concentrations of ions that were not measured in this study, including Na, Cl, HCO_3 and K. The highest TDS occurred at DW1-DW5 in the Tasi-Tolu Area, west of Dili, a small area immediately west of Dili that is largely separated from the Comoro Fan by a bedrock sill. The water there tastes noticeably salty and only the shallowest well returned TDS < 1000. All wells had high pH and two wells exceeded the typical drinking water maximum pH of 8.5 (WHO 2011a).

The TDS and pH in the Tasi-Tolu area are consistent with high ionic concentrations resulting from saltwater intrusion, which was suggested based on a previous time-domain electromagnetic survey that identified a conductive response in the Tasi-Tolu region with a resistive pod of presumably freshwater close to the surface (Ley Cooper and Munday 2011). However, the only well in the study area to exceed a 250 mg/L limit for sulfate in groundwater (Vrba 2002) was also in the Tasi-Tolu catchment. That well (DW1—sulfate = 1500 mg/L), also has high concentrations (3.5 mg/L) of fluoride and high salinity

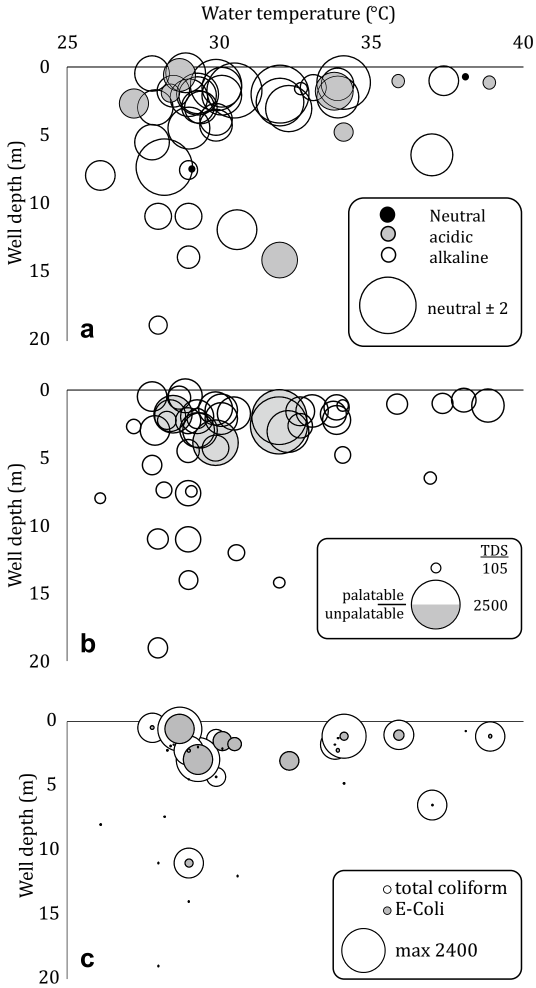

Fig. 5 Relationships among temperature, depth, dissolved solids, pH and coliform bacteria. **a** pH—circles scaled by deviation from neutral. **b** TDS—circles scaled by concentration, TDS > 1000 coloured unpalatable; **c** total coliform and *E. coli*, circles scaled by concentration

(Fig. 6). Both fluoride (Edmunds and Smedley 2013) and sulfate (Vrba 2002), along with other salts, occur in areas of intense evaporation. Elevated sulfate concentrations in natural groundwater can result from dissolution of evaporites (e.g., gypsum, anhydride), or groundwater interaction with metallic sulphide minerals (Vrba 2002, unlikely in this instance). The DW1 well is located on the margin of the ephemeral Tasi-Tolu lake, which is a low-slope area of intense evaporation. Low slopes contribute to slow groundwater flow rates, increasing the potential for groundwater contamination. The salinity and conductivity (Ley Cooper and Munday 2011) of the Tasi-Tolu aquifer may, therefore, be partly authigenic and partly related to saline intrusion.

Nitrite, nitrate, and ammonia

Nitrite and nitrate highs were found principally along the coastline east of the Comoro River (Fig. 7), where levels reached 9 mg/L (nitrite, exceeding WHO 2011a guidelines) and 7.7 mg/L (nitrate). Well DW29, located close to the rangefront, also had elevated nitrate and nitrite, but with reversed importance of nitrate versus nitrite. The coastal nitrate high and nitrite pollution occur in an area occupied by embassies and the longer-established hotels (embassy district in Fig. 7). The embassy district is relatively free of animals, and remote from outcrops of metabasic rocks that might contribute nitrate by dissolution (e.g., Tredoux and Talma 2006). One possible source is the use of mineral fertilizer for lawn maintenance (Kowal and Polik 1987). Additionally, nitrite might form in this environment either by stagnation of nitrate rich water in galvanized pipes, or as a by product of poorly controlled water disinfection in water and waste management and disposal systems (e.g., Kowal and Polik 1987; Wakida and Lerner 2005; WHO 2011b). Given that the source water is not nitrate rich, the latter seems more likely. Thus, the water management systems in these establishments may be contributing to local moderate nitrite pollution.

The nitrate pollution in the area of DW29 is probably attributable to domestic grey water and livestock (Fig. 4). The area is located in the most inland part of the low-slope, Colmera Plain interfan area, where very shallow groundwater maintains a permanent wet natural ground surface. Drains cut to lower the water level in this former swamp carry blue-grey water that is contaminated by domestic washing and livestock.

Ammonia levels are generally low, and even the highest ammonia concentrations, in Colmera CBD area, were substantially below the 0.2 mg/L that is the typical upper limit for natural groundwater (Fig. 7).

Iron and manganese

Our survey detected Mn levels ranging from 0 to 13.2 mg/L (Fig. 8), greatly exceeding the typical concentrations found in drinking water (c. 0.1 mg/L) and well in excess of health-based guidelines for Mn in drinking water (0.4 mg/L) (WHO 2011a). A single litre at these highest levels would exceed the maximum recommended daily dietary intake of manganese (11 mg). Dissolution of geologic Fe and Mn occurs most effectively in acidic, oxygen poor groundwater. We note that some of the observed Mn contamination reported with low pH, especially at the

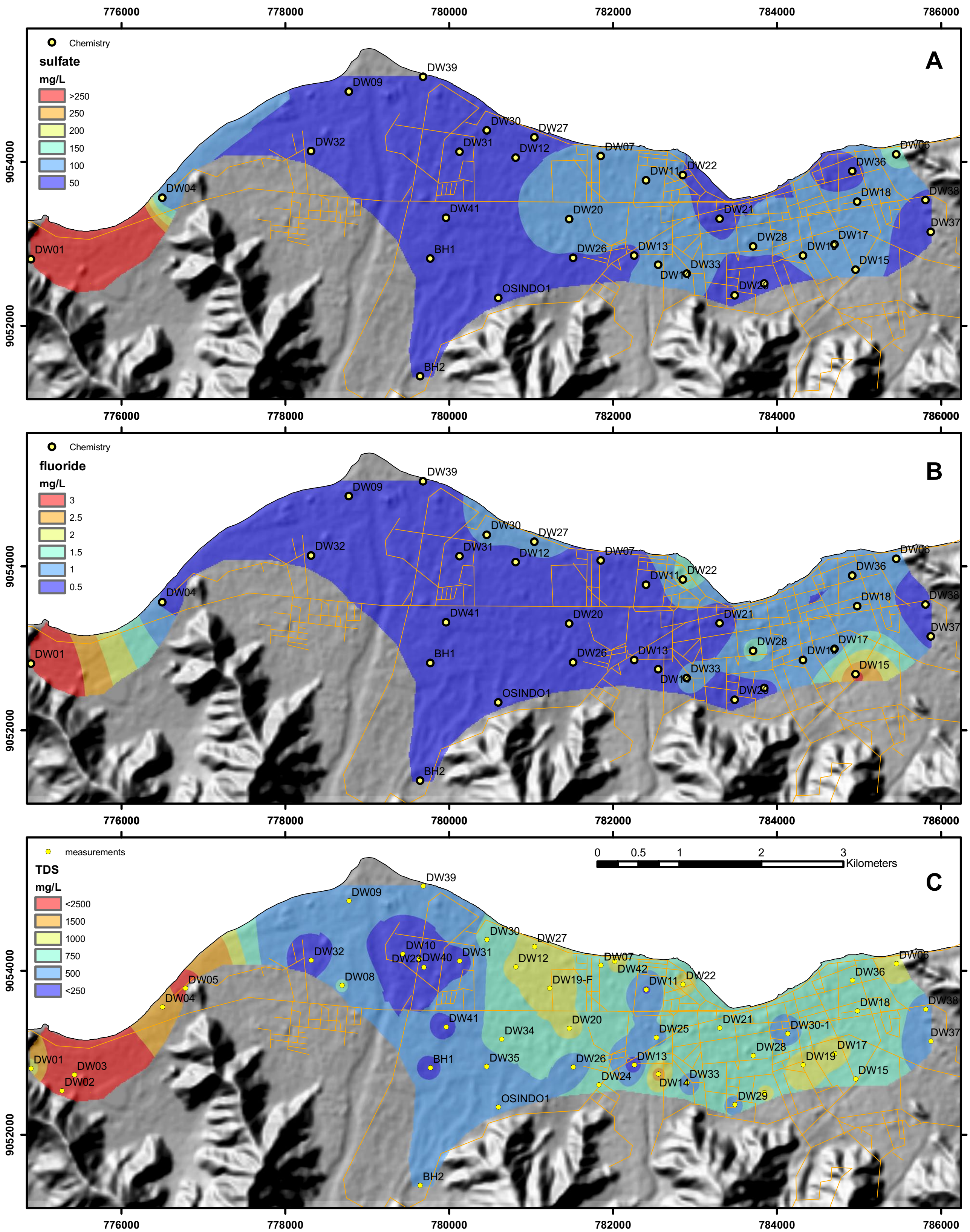

Fig. 6 Sulfate (**a**), fluoride (**b**) and total dissolved solids (**c**) concentrations in the unconfined aquifer. Note the prominent high concentrations of all three at DW1 on the margin of Tasi-Tolu Lake, and of TDS and Fluoride around DW15 on the eastern margin of the Comoro Fan

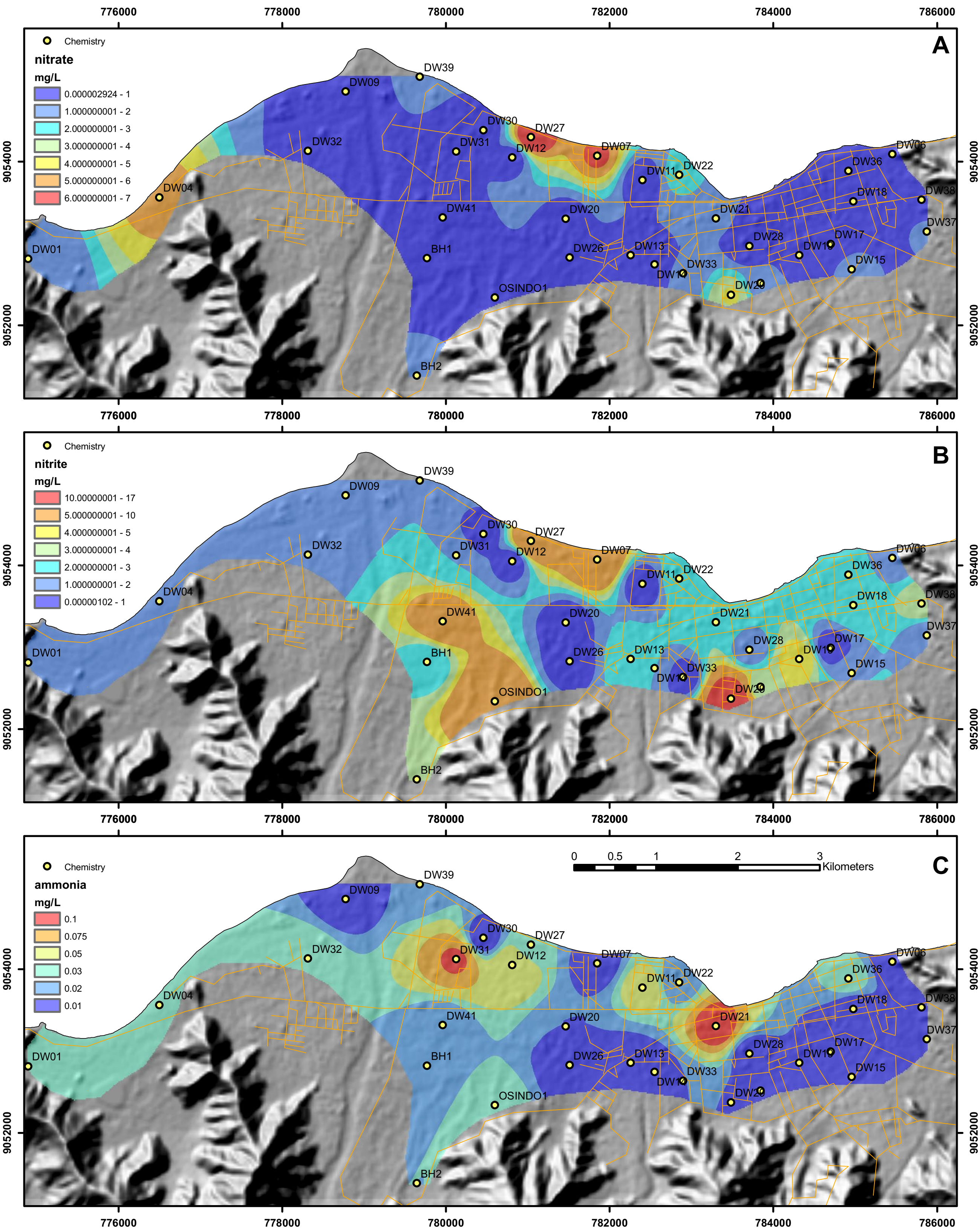

Fig. 7 Nitrate (**a**), nitrite (**b**) and ammonia (**c**) concentrations in the Dili unconfined aquifer

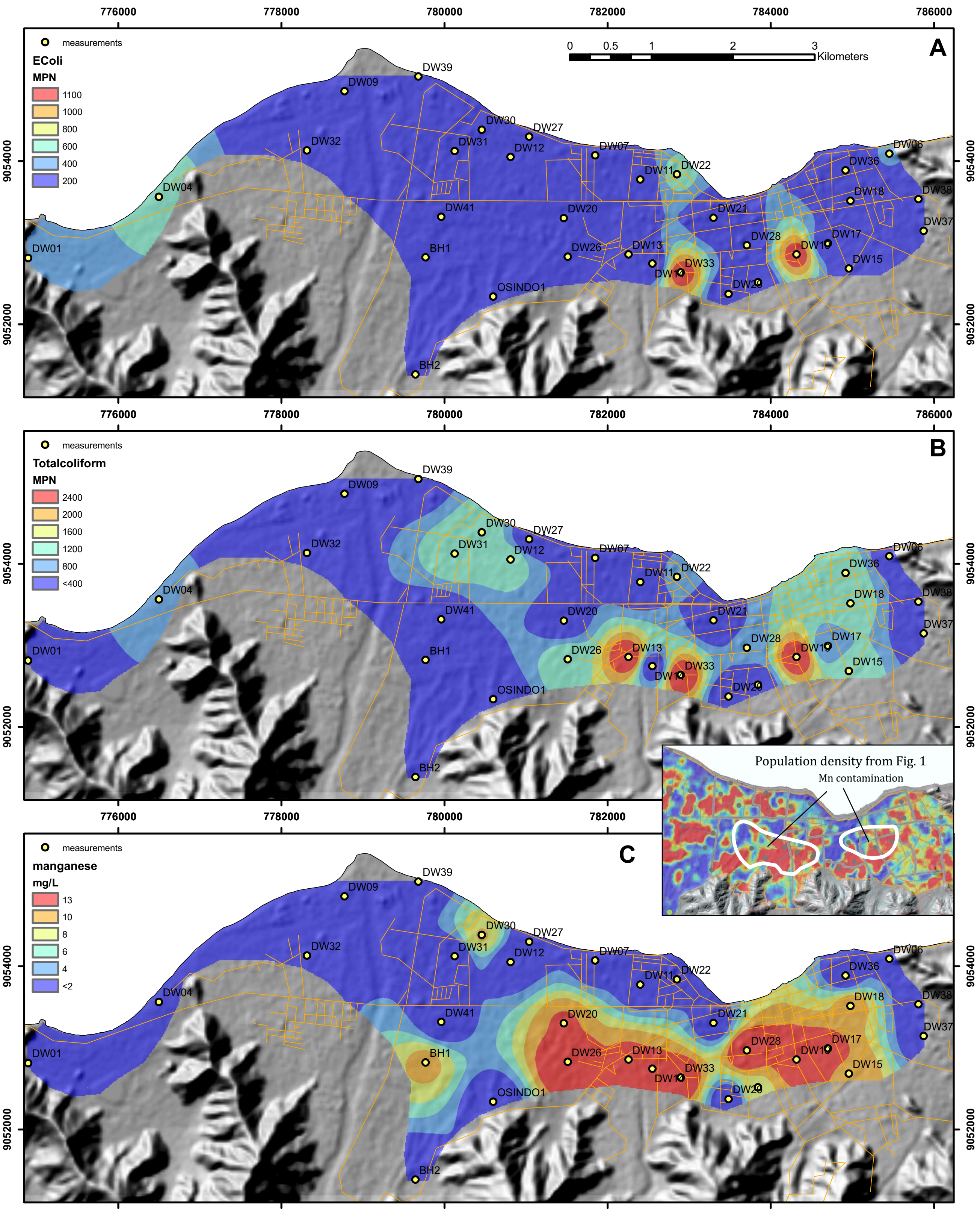

Fig. 8 *E. coli* (**a**) and total coliform (**b**) shown for comparison with Mn (**c**)

rangefront, but otherwise there was a generally poor relationship between pH and Mn.

Microbiological parameters—*E. coli* and total coliform

Non-geologic sources of Mn that may be relevant in Dili include industrial effluent and sewage. The latter would be most clearly indicated by microbiological contamination of groundwater. Of 33 samples tested, 18 returned positive for coliform bacteria (55%), including 13 (40%) positive for fecal coliform (*E. coli*). The contamination was widespread, but generally reflected population density patterns and was worst in eastern part of the Dili Plain (Fig. 8). Concentrations of total coliform bacteria and manganese are strongly spatially correlated. Nine of 13 samples (70%, including DW13 - Fig. 4a) returning total coliform > 400 MPN had elevated Mn (> 0.4 mg/L), compared with only 4 of 20 low coliform samples (20%). The contamination is spatially associated with the smaller alluvial fan systems in eastern Dili, and its western limit approximately follows the contours of the foot of the Comoro fan, where it probably interfingers with the smaller fan. These contaminated areas are generally swampier and finer grained than western areas of Dili.

Temperature also seems to be a factor in coliform contamination. The highest concentrations of coliform bacteria in the Dili groundwater occur within a temperature range of 28–29 °C (i.e., some of the coolest wells). Furthermore, even though several deeper wells had as cool or cooler temperatures, all but two coliform bacteria-contaminated wells were less than 4.5 m deep (Fig. 5c). In part this may reflect the preponderance of shallow wells. Wells less than 4.5 m deep accounted for 70% of the wells that we observed (33/47), and 72% of the wells that we tested for coliform bacteria (24/33). Nevertheless, 67% (16/24) of the shallow wells were contaminated with coliform bacteria, versus only 22% of the deeper wells (2/9).

Discussion

Contaminated groundwater can be a major vector of disease (Montgomery and Elimelech 2007), even in developed countries (Risebro et al. 2012), and contribute to social and economic losses that maintain a cycle of loss through long term damage to health and productivity. Rapid development of appropriate sanitation policy is, therefore, of particular concern for groundwater quality management in developing countries, but the success of this is predicated on: (1) the establishment of baseline data (Back et al. 2018), and (2) development of a systems-thinking approach (e.g., Hipel et al. 2008) to holistic water resource management.

The start of a baseline

We set out to begin the task of establishing a water quality baseline for the Dili aquifer, and to evaluate the effect of geological and socio-economic factors on shallow groundwater quality. Our results provide a snapshot of the factors affecting water quality in this small but developing city.

Our admittedly few data show that Dili's shallow unconfined aquifer is a heterogeneously polluted resource that is accessed by numerous, unregulated dug wells. This study does not include several important parameters, such as arsenic, sodium, chloride, magnesium, calcium, and potassium. We note that Na and Cl especially will need to be monitored to assess the level of seawater intrusion that is suggested by zones of elevated TDS, but nevertheless we do not consider that their absence diminishes the impact of the results presented here and we will be including these parameters in future studies. The physical characteristics of the water are generally favourable for drinking, with acceptable pH and TDS except for wells in the saline, evaporative environment of the Tasi-Tolu area previously identified by Ley Cooper and Munday (2011). With the exception of Tasi-Tolu, physical characteristics such as TDS improve and temperature decreases with increasing depth (Fig. 5).

Nitrogenous contaminants were surprisingly low considering the prevailing water and sanitation practices. Compared with other rapidly growing Asian cities, Dili's nitrate levels were among the lowest—1.32 mg/L compared with a range of 0.4–55 in large cities of Latin America, Africa, and Asia (Haque et al. 2013; Lawrence et al. 1998; Nlend et al. 2018). However, these other studies were the result of longer-term monitoring, which has not yet been undertaken in Dili. This survey occurred early in the rainy season and characteristics may vary significantly across seasons. The exceedance of nitrite guidelines in the embassy district suggests that affluent practices, such as lawn cultivation, or localised water and waste management and disposal systems (e.g., Kowal and Polik 1987; Wakida and Lerner 2005) are contributing to water quality problems.

Densely populated, poorly served areas are predictably polluted by coliform bacteria. The greatest coliform contamination occurred where the geomorphic and piezometric gradient was lowest and the groundwater was closest to the surface (compare Figs. 1, 8). The shallow depth of coliform contamination and the reduced contamination of deeper wells, even within the same socio-economic context, suggests that direct leakage of bacteria through the latrine-aquifer interface, especially at close spacing to wells (e.g., Fig. 4), is responsible for coliform contamination.

Contamination is enhanced by survival rates at cooler wells (e.g., Jamieson et al. 2004).

Mn levels reach more than 30 times the recommended levels over the broad region of coliform contamination. Several suites of fine-grained Timorese rocks contain abundant Mn nodules (Audley-Charles 1965; Idrus et al. 2013; Margolis et al. 1978) and may be supplying lithogenic Mn oxides to the Dili region. Excessive bacterial activity relating to coliform contamination may lower the redox potential, reducing the Mn oxides and allowing Mn to migrate into wells in the shallow aquifer (Gounot 1994). This is particularly likely in low-gradient interfan settings where: (1) fine-grained Mn and organic-rich sediments are preferentially deposited, (2) groundwater is slow-flowing and poorly aerated, and (3) smaller grain sizes increase the survival rates of enteric bacteria (Howell et al. 1996; Jamieson et al. 2004).

Combined bacterial and chemical contaminants (but not viruses) are usually attenuated to potable levels at a disposal-to-well distance of 35 m, with bacterial contamination generally attenuated by 15 m (Graham and Polizzotto 2013). However, safe offsets of this scale are impractical to implement in a city as densely populated as Dili. The preferential concentration of coliform bacteria in some of the coolest wells is consistent with many studies that report enhanced survival times for fecal coliforms in lower temperature water (e.g., Jamieson et al. 2004 and references therein), suggesting that such bacteria should decline more quickly with distance from the contaminant source if temperatures are higher. The temperature dependence suggests that the groundwater temperature increase that accompanies urban hard landscaping (Taylor and Stefan 2009) may be advantageous in Dili, at least in this respect.

Management of resource quality

Future management of the Dili aquifer needs to be informed by repeated, appropriately funded case studies that expand on this preliminary work and document the spatial and temporal scales of interaction across component systems (e.g., Back et al. 2018). This study does not constitute a complete baseline; a proper baseline will need to include (1) high resolution mapping of all water supply and sanitation points; (2) development of a database of contaminated sites, including but not limited to fuel stations, maintenance yards, quarries, and dumping sites; and (3) repeated measurements over a full seasonal cycle. Eastern Dili is clearly a priority area for baseline data surveys.

The Dili aquifer system is small and its high productivity endows it with a level of responsiveness that renders it both vulnerable and resilient, depending on management. The water quality issues highlighted here illustrate how vulnerable the near-surface groundwater resource is to environmental degradation. The hydraulic conductivity of the aquifer, though not well constrained, is probably high (Pinto et al. 2017), so the pollution of the resource should respond quickly to measures that reduce contamination sources.

The results of this study indicated that the Timor-Leste government need to develop a major policy focus on improving reticulated water and sanitation access for the urban poor, such as has occurred in Cambodia (WHO 2014). Areas such as Tasi-Tolu, where deep wells are not an option, should be prioritized for reticulated water supply. Increasing well depth is likely to have other effects, such as allowing leakage between aquifers, so is not an endgame solution. Water supply and waste disposal infrastructure in the embassy district needs to be evaluated to understand the source of nitrite contamination in that area, a process that may require intergovernmental engagement.

Towards a system thinking approach to groundwater management in Dili

Groundwater forms part of a complex social-natural resource system that needs to be managed within the context of the (often dynamic) physical, climatic (Fowler et al. 2003), socio-political (Barnaby 2009), economic (Gill et al. 2017), ecological (Deacon et al. 2007) and cultural factors (Jennaway 2008) that characterize the resource area. Our concept of this interdependent system in Dili is summarized as an influence diagram in Fig. 9. This conceptualization suggests that Dili must transition from existing practices, where the aquifer is managed as an increasingly stressed common-pool resource (e.g., Madani and Dinar 2012), towards integrated systems management. This transition must co-evolve with economic and population growth that stresses the groundwater system if Timor is to mitigate further rapid anthropogenic degradation of groundwater quality.

The Government of Timor-Leste is presently in the process of drafting a new groundwater policy, which provides an opportunity to embrace systems-thinking. A successful policy will require the government of Timor-Leste to manage the competing land-use pressures, including quarrying in the recharge zone, industrial activity on the Dili Plain, drinking water provision and waste water disposal in built up areas, whilst continuing to meet sustainable development and economic goals. Presently, the piped water system, which accesses deeper aquifers, is not growing at a pace suitable for the demands of a growing city (Timor-Leste WASH stakeholders 2014), so the relatively unregulated use of the shallow aquifer as a common-pool resource is likely to continue.

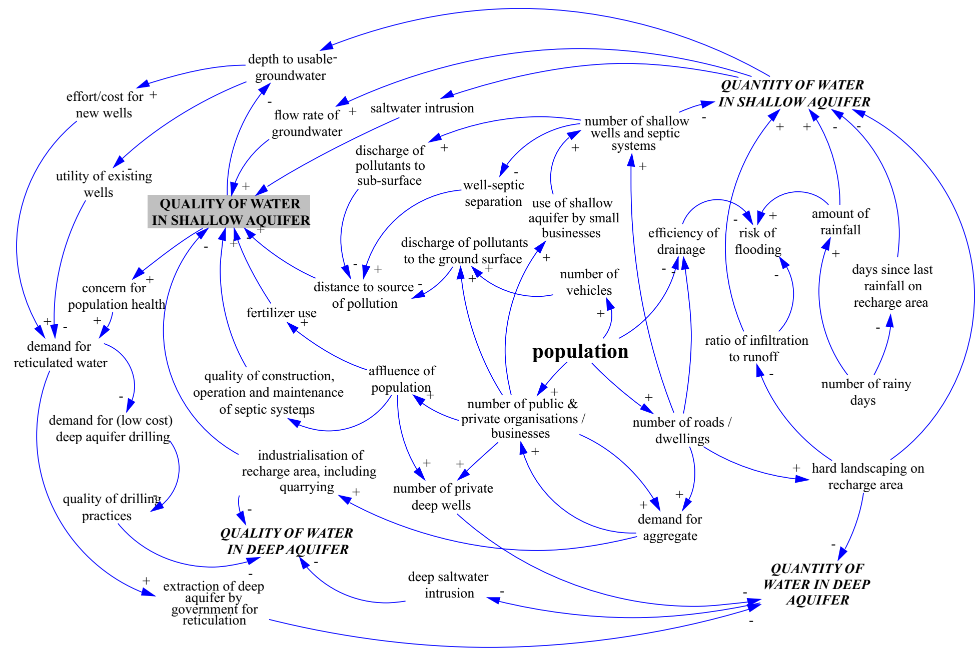

Fig. 9 Influence diagram showing the interconnections between social and physical systems surrounding the Dili aquifer. Our focus is on the quality of water in the shallow aquifer, but it is unrealistic to try and separately manage quality and quantity in the different aquifers. Arrowheads indicate the direction of influence. Positive (+) symbols indicate that linked factors are driven in the same direction—either both up or both down. Negative (−) symbols indicate that linked factors are driven in opposite directions—when one goes up, the other goes down, and vice versa

Conclusions

Dili's unconfined aquifer, which supplies water to much of its population, is threatened by quality issues arising from natural factors and poor management.

- Saline groundwater in areas like Tasi-Tolu may arise from a combination of intense evaporation at the surface (a natural effect) and seawater intrusion in the subsurface, which may be exacerbated by depletion of the freshwater resource.
- The Colmera Plain exhibits moderate to severe fecal coliform contamination that is associated with potentially toxic Mn concentrations. These occur in low geomorphic and potentiometric gradient areas with very shallow groundwater and result from seating of pit latrines in the clay rich, very shallow saturated zone, close to well sites.
- Nitrate and nitrite pollution occur in the low-gradient areas, where they may be attributed to domestic waste, and also in the affluent embassy district, where they may be related to poorly maintained water distribution systems or excessive fertilizer use on lawns.
- In general, deeper wells contain better quality water, and shallow cool wells are most problematic.

Effective management of the common-pool, unconfined aquifers in Dili and elsewhere in Timor-Leste will be contingent on not only developing appropriate regulations regarding physical use of the aquifer, but on understanding the complex social context of the aquifer resource.

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