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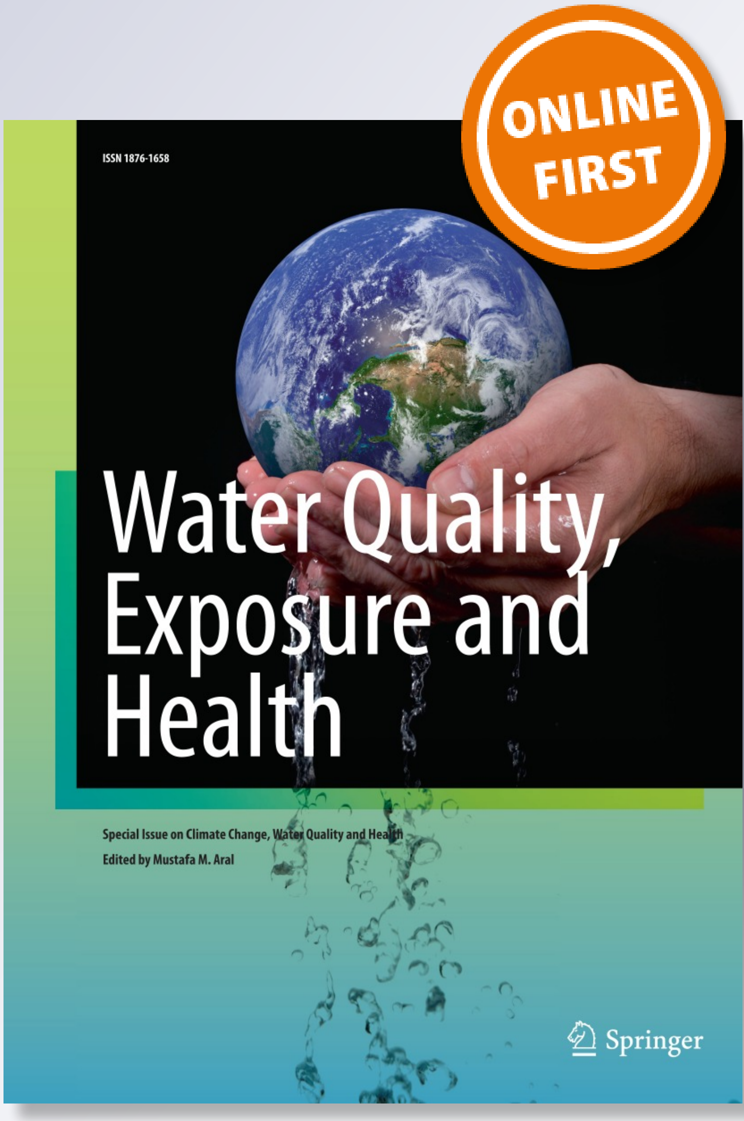

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ORIGINAL PAPER

Physicochemical and Bacteriological Water Quality Across Different Forms of Land Use on the Mahafaly Plateau, Madagascar

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Abstract The sub-arid southwest of Madagascar is one of the world's biodiversity hotspots combined with exceptional poverty and high risk of further temperature increase that will aggravate the living and health conditions of the people. As bases for future water management, we measured the physicochemical and microbiological quality of water sources across different forms of land use in the protected Tsimanampetsotsa National Park, and the agricultural and pastoral regions of the Mahafaly plateau on limestone and the coastal plain on sand during the dry and wet season of 2012–2013. We investigated spatial and seasonal variation of water characteristics and their relationships with bacterial contamination. Portable meters were used for the physicochemical measures. The compact dry method was used for microbial analyses. The pH was neutral to slightly alkaline and within the permissible limits of WHO and Malagasy standards. Electric conductivity (EC) and total dissolved solids (TDS) were very high and above the permissible limits in the coastal plain, moderately high in the park and low on the plateau. The concentrations of nitrogen components (NH_4, NO_3 and NO_2) were high in the rainy season, with the highest concentrations in wells. Phosphate concentration was high throughout the study area. Total coliforms, *Escherichia coli*, *Salmonella* spp. and *Vibrio* spp. were present throughout the study area year-round, representing a serious health hazard. Their concentrations were not correlated with any physicochemical characteristics in any systematic fashion that would allow to use the physicochemical characteristics as proxy for microbial contamination. Poor sanitary conditions are the principal causes of the water contamination that could be reduced substantially by simple behavioural changes of the local human population. The finding that water temperature in wells of the plateau and to a lesser extent of the coastal plain increases during the hot wet season indicates a substantial contribution of surface rather than subterranean water to the water available for human and livestock consumption. This limits the options for future increase of water consumption by people, livestock and agriculture in the region.

Keywords Tsimanampetsotsa National Park · Sub-arid climate · Water quality · Water pollution · Bacteria · Total coliforms

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Introduction

Consumption of unsafe water is a serious problem for public health especially in developing countries. The situation is aggravated in areas with limited water supply where almost any source of water is used for human consumption and to water livestock (WHO 2004; Montgomery and Elimelech 2007). Madagascar, ranking number 151 on the Human Development Index, is no exception. Especially in the dry south-western region of Madagascar access to drinking water constitutes one of the fundamental problems for the human population and their livestock (Ramampiherika and Ralijaona 1995). Up to 2005, only 13 % of the human population had access to safe drinking water in rural areas of Madagas-

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car (WHO and UNICEF 2006; World Bank 2014). While the situation has been improved over the last decade, there is no standardized monitoring of water quality in most rural areas of Madagascar and clean water remains a major problem for the rural population (Mattern and Ravelomandeha 2012). Apart from the obvious scarcity of water, improvement of the health conditions are hampered by the lack of awareness of health risks by the local population. In the perception of local people water quality is related to salinity rather than organic pollution (Commune of Beheloka 2005).

As part of a study on sustainable land management for parts of the dry south-west of Madagascar (SuLaMa 2011; Brinkmann et al. 2014), the goal of this study was to determine the physiochemical and bacteriological characteristics of water from different types of water sources in relation to geological and anthropological conditions. Specific objectives were to (1) determine whether or not water characteristics reflecting possible hazards to human health are distributed evenly in the region or reflect regional characteristics, (2) determine whether or not different types of water sources are subject to different forms of contamination and (3) verify whether or not bacterial contamination is linked to salinity or other physicochemical characteristics.

Materials and Methods

Study Area

The study area is located in south-western Madagascar. From west to east, it covers the Mahafaly coastal plain, the Tsimanampetsotsa National Park and the Mahafaly Plateau between 23°47′–24°42′S and 43°39′– 44°25′E (Fig. 1).

The region is characterized by a semi-arid climate with an annual rainfall varying from 300 mm in the coastal plain to 600 mm on the plateau. The rainy season starts in December and ends in March with a dry season from April to November. Rainfall is highly unpredictable with high spatial and inter-annual variation (TMD 2011), and seems to have shifted by about two months during the last few years (Battistini 1964; Ratovonamana et al. 2011, 2013). There are no apparent rivers and the water availability depends primarily on rainfall with some subterranean aquifers originating further inland (Guyot 2002; Rajaobelison et al. 2003).

The coastal plain is limited by the Mozambique Channel in the west and the cliff of the plateau in the east. It is covered with quaternary sand dunes of different generations and forms a continuous band of variable width (from 1.5 to 15 km) before the Mahafaly limestone massif rises to a height of about 130 m above sea level, forming the Mahafaly Plateau. The Mahafaly Plateau stretches a few kilometres inland from the sea and measures 150 km in length and 20–50 km in width. The eastern part consists of chalky limestone originating from the middle Eocene, unfavourable for karstification. The western part is composed of biodetritic Eocene limestone with many caves and sinkholes. The Tsimanampetsotsa National Park, located in the western part of the plateau, contains hundreds of caves and sinkholes. Many of them contain water (Guyot 2002; Dobrilla 2013).

The Human Dimension

Local people depend on wells and natural water sources (e.g. sinkholes, sources and ponds) for domestic use. Water points are used for drinking, washing and bathing. Often, these activities are practiced close to or directly inside the water source and many of them are used by humans and livestock simultaneously. Sanitation is a major challenge in this region as most of the people do not use any sanitation facilities. Thus, water sources are exposed to organic pollution and are prone to bacterial contamination. This quasi systemic water contamination constitutes a major problem for human health in this area (Guyot 2002; Ramampiherika and Ravaloson 2010). In particular, diarrhoea is among the most frequent diseases in this region (Commune of Beheloka 2005). In addition, some water sources have high salt concentrations due to the vicinity of the sea and a soda lake (Lac Tsimanampetsotsa) situated on the coastal plain. In the perception of the local people, water quality is more characterized by the taste and salinity of the water than by influx of organic waste and subsequent bacterial development.

Types of Water Sources

Water is used from different types of natural or anthropogenic sources. Despite the presence of water in caves and sinkholes, wells represent the main source of water for domestic use. Wells can be open or covered, dug directly into the ground or have a specific border (made of rocks or concrete, with or without a nozzle). In most cases water is hauled to the surface using a bucket with a long rope left on the ground, thus allowing contamination from the surroundings (Fig. 2). Some wells in the coastal plain had been drilled by UNICEF in 2000 (UNICEF well). They are sealed and water is pumped with hand pumps (Guyot 2002); most of them are no longer functional (as of 2013). Due to the geomorphology and human activities, the different types of water sources are distributed unevenly among the coastal plain, the park and the plateau (Table 2).

Sampling Procedure

In total 28 wells, six caves, five sinkholes, two UNICEF wells and one spring/seep were sampled (Fig. 2, Appendices S1, S2). Physicochemical parameters were measured twice per season, in August–September 2012 for the dry season and

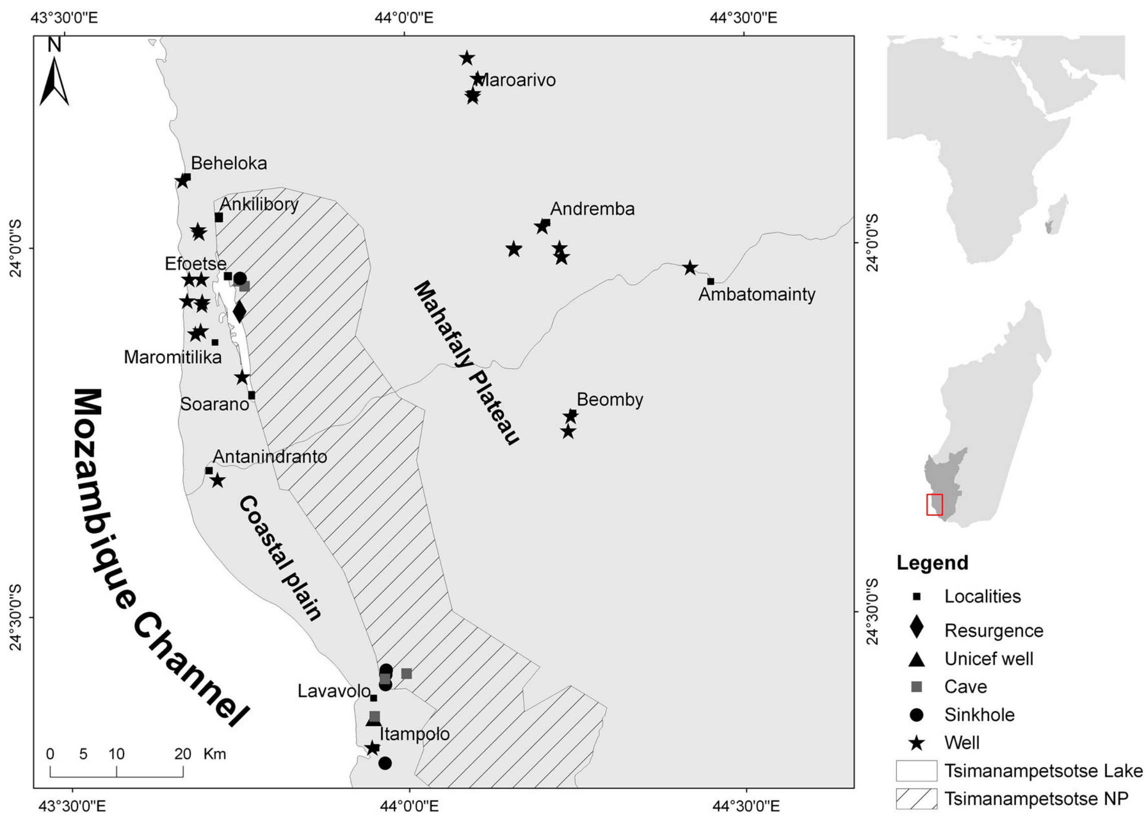

Fig. 1 Study area and sampling sites in south-western Madagascar. Fourteen wells, two Unicef wells, one cave and one sinkhole were sampled in seven villages of the coastal plain (Beheloka, Ankilibory, Efoetse, Maromitilika, Soarano, Lavavolo and Itampolo). Fourteen wells were studied in four villages of the Mahafaly plateau (Maroarivo, Andremba, Ambatomainty and Beomby). Three caves (Mitoho, Andranoilove and Andriamaniloke), one sinkhole (Vintany Nord) and one spring (Mande) were studied in the Efoetse sector of the National Park. Three caves (Anjamanohatse, Anjamanohatse Masay and Ranofotsy) and two sinkholes (Lalia and Tehafe) were sampled in the Itampolo sector of the National Park

in February–March 2013 for the wet season. Measurements were performed directly in the field at 9 am. The data present the means of two independent measurements. Sampling containers were properly cleaned before use and rinsed with the water to be sampled before sampling.

Bacteria analyses were carried out once per season, sterile new plastic bottles with hard plastic screw caps were used for sample collection. The samples were placed in cooler box while being transported to the laboratory. All water samples were analysed within 3 h.

Sample Analysis

Physicochemical parameters were measured with portable meters. Temperature, dissolved oxygen (DO) and oxygen saturation were measured with a Voltcraft DO-100 dissolved oxygen meter. The pH, the EC and the TDS were assessed with an electronic pH and EC meter of Hanna. Ammonia, nitrate, nitrite, phosphate and iron analyses were performed by using specific reagents and the photometer HI83205 of Hanna.

Bacteria analyses were performed with the compact dry method. Three different types of HyServe compact dry plates were used. The EC plates were used for *Escherichia coli* and total coliforms. The VP plates were used for *Vibrio* spp. The *SL* plates were used for *Salmonella* spp. With a sterile pipette, 1 ml of the water sample was dropped onto the plate and all plates were incubated at 35 ± 1 °C for 24 h while the liquid samples self-diffused evenly over the whole plate. The grown colonies were pigmented with different colours, developed by chromogenic substrates and redox indicators and the type of bacteria were identified by its colour (Kodaka et al. 2006). The bacteria count was performed using a magnifying glass. If more than 600 colonies had developed, the number of colonies could no longer be counted reliably. For these cases we set the number to 700 arbitrarily to allow for statistical analyses.

Data Analyses

Data were analysed for deviation from normality. Since most data deviated from normality and the different types of water

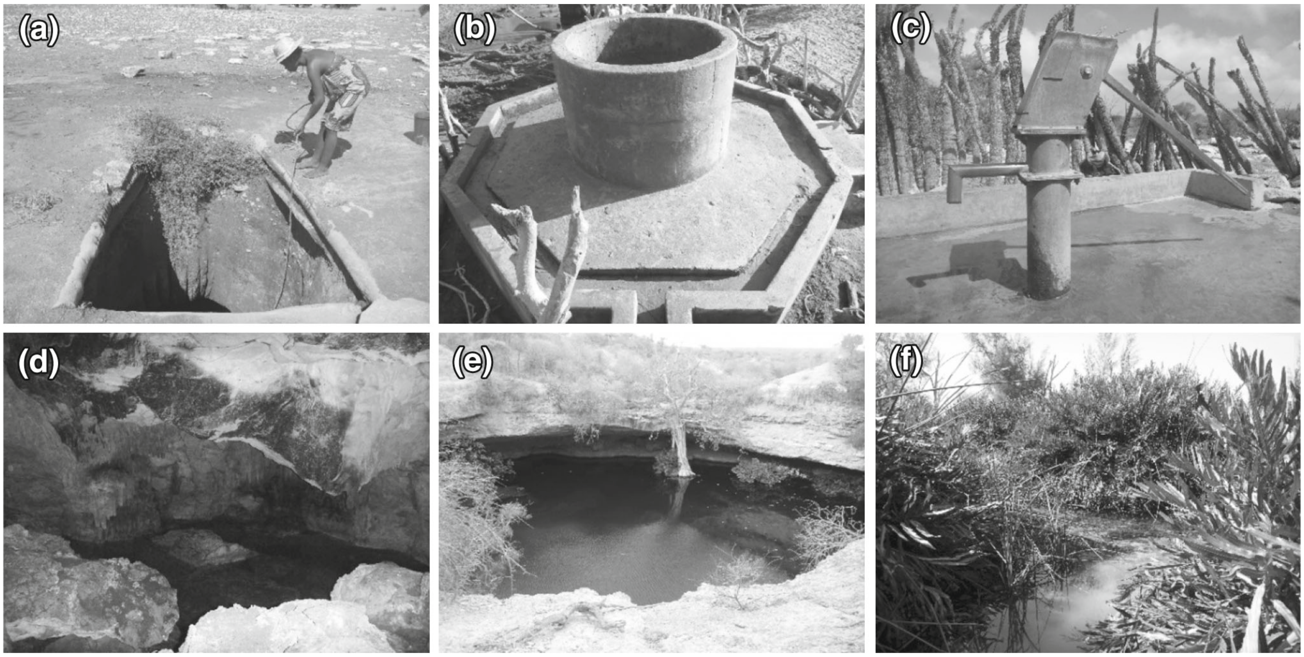

Fig. 2 Examples of the types of water sources sampled. **a, b** Wells dug directly in the ground or reinforced with a concrete or rocks and with an uncovered outlet. Well water is drawn to the surface using a bucket with a long rope thus allowing contamination from the surroundings; **c** sealed, established well including a hand pump constructed by UNICEF (UNICEF well); **d** cave; **e** sinkhole; **f** spring

bodies were not present in all areas, we use univariate non-parametric statistical test variables. Kruskal–Wallis analysis of variance for independent samples (for regional differences of physicochemical parameters), Wilcoxon test for related samples (for seasonal differences) and Mann–Whitney U test for independent samples (for regional differences of bacteria counts).

Water quality parameters were compared to three different standards, as defined by the WHO (2011), the Madagascar Code Eau (1999) and the EPA (2013a,b). In addition, the groundwater classification of Prakash and Somashekar (2006) was used for interpretations of the links between EC (as a measure of the total ion/salt concentration) and the TDS (Table 1).

Table 1 Groundwater quality classification of Prakash and Somashekar (2006)

EC (μS cm^{-1})	Classification	TDS (mg l^{-1})	Classification
<250	Excellent	<1,000	Non saline
250–750	Good	1,000–3,000	Slightly saline
750–2000	Permissible	3,000–10,000	Moderately saline
2,000–3,000	Doubtful	>10,000	Very saline
>3,000	Unsuitable		

EC electric conductivity at 25 °C, *TDS* total dissolved solids

Results

Regional Differences in Physicochemical Parameters

The results for the various abiotic parameters are summarized in Tables 2 and 3. The raw data are listed in the supplementary material (Appendices S1 and S2).

Wet Season

The water temperature ranged from 26.7 to 28.6 °C (mean ± standard deviation: 27.5 ± 0.46 °C) in the coastal plain, from 26.9 to 30.0 °C (28.5 ± 1.1 °C) in the national park, and from 25.2 to 30.2 °C (26.9 ± 1.6 °C) on the plateau. These differences were significant (Kruskal–Wallis Analysis of Variance: $\chi^2 = 7.00$, df = 2, $p < 0.05$). The highest values were measured in the coastal plain in the UNICEF well and in the spring in the park.

The mean values of pH ranged from 7.4 to 8.0 in the coastal plain (7.6 ± 0.2), from 7.0 to 7.6 in the national park (7.3 ± 0.2) and from 7.0 to 8.1 on the plateau (7.4 ± 0.3), thus indicating slightly alkaline conditions. The pH did not differ between regions ($\chi^2 = 5.26$, df = 2, $p > 0.05$). All of the samples were within the permissible limits of the various standards.

The DO varied from 1.6 to 8.3 mg l^{-1} in the area with a median of 4.6 mg l^{-1}. Across all three areas, the oxygen saturation ranged from 3.7 to 55.4 % with a median of 12.0 %.

Table 2 Means and standard deviations of the physical water parameters: Temp, pH, DO, O_2

Area	Type	Season	Temp (°C)	pH	DO (mg l^{-1})	O_2 (%)
Coastal Plain	Well (wet: $N = 14$; dry: $N = 10$)	Wet	27.48 ± 0.50	7.63 ± 0.17	5.1 ± 1.1	13.2 ± 3.0
		Dry	26.44 ± 0.77	7.36 ± 0.18	5.1 ± 1.2	12.8 ± 2.9
	UNICEF well ($N = 2$)	Wet	28.23 ± 0.46	7.61 ± 0.02	7.7 ± 0.6	20.3 ± 1.3
		Dry	27.85 ± 0.21	7.45 ± 0.10	7.0 ± 0.2	18.4 ± 0.6
	Cave ($N = 1$)	Wet	27.50	7.53	4.0	10.5
		Dry	27.27	7.29	6.5	16.9
	Sinkhole ($N = 1$)	Wet	27.20	7.67	2.4	5.5
		Dry	27.40	7.68	7.9	20.4
Park	Cave ($N = 5$)	Wet	28.80 ± 0.95	7.27 ± 0.24	4.0 ± 1.7	11.0 ± 5.7
		Dry	28.46 ± 0.54	7.30 ± 0.12	5.7 ± 0.9	15.1 ± 2.3
	Sinkhole ($N = 4$)	Wet	27.75 ± 1.06	7.31 ± 0.06	4.4 ± 0.6	11.3 ± 1.3
		Dry	27.33 ± 1.13	7.35 ± 0.03	5.2 ± 0.2	13.4 ± 0.8
	Spring ($N = 1$)	Wet	29.70	7.37	6.5	17.10
		Dry	28.85	7.35	6.5	15.9
Plateau	Well (wet: $N = 14$; dry: $N = 11$)	Wet	26.92 ± 1.62	7.37 ± 0.3	4.7 ± 2.3	15.9 ± 13.4
		Dry	24.18 ± 2.01	7.27 ±0.26	5.1 ± 3.9	12.2 ± 3.0
Acceptable limit			NS	6.5–8.5*	NS	NS

Temp temperature, *DO* dissolved oxygen, O_2 oxygen saturation, *NS* no standard
* WHO (2011)

Neither DO nor oxygen saturation differed between areas ($\chi^2 < 1.8$, df = 2, $p > 0.05$). In the coastal plain, the highest DO was recorded in the UNICEF well while the highest oxygen saturation was measured in the sinkhole. The spring had the highest DO and oxygen saturation in the national park.

The two measures of salinity, EC and TDS, showed marked differences between areas. In the coastal plain, EC varied from 979 to 54,384 $\mu S\ cm^{-1}$ with a median of 8,574 $\mu S\ cm^{-1}$; 93 % of the wells and one of the two UNICEF wells (the UNICEF well at Itampolo) exceeded the acceptable limits of standards. The water is classified as unsuitable in wells, doubtful in UNICEF wells and permissible in sinkholes and caves. In the national park, the EC ranged from 1,051 to 3,162 $\mu S\ cm^{-1}$ with a median of 2,395 $\mu S\ cm^{-1}$. The spring, 60 % of the caves and 25 % of the sinkholes exceeded the permissible limit. The water was classified as permissible in the sinkhole, doubtful in the cave and unsuitable in the spring. On the plateau, the EC ranged from 13 to 2,475 $\mu S\ cm^{-1}$ with a median of 341 $\mu S\ cm^{-1}$ indicating permissible water quality, 14 % of the wells exceeded the permissible limits. The difference between regions is highly significant (Kruskal–Wallis analysis of variance: $\chi^2 = 20.45$ df = 2, $p < 0.001$).

In the coastal plain, the TDS varied between 490 and 27,136 ppm with a median of 4,296 ppm; 93 % of the wells and the UNICEF well of Itampolo exceeded the permissible limit. Water was non-saline in the caves, slightly saline in the UNICEF wells and moderately saline in the wells. In the park, TDS ranged from 533 to 1,582 ppm with a median of 1,197 ppm. The spring, 60 % of the caves and 25 % of the sinkholes exceeded the permissible limit. On the plateau, the TDS ranged from 17 to 1,239 ppm with a median of 170 ppm indicating non-saline water. 14 % of the wells exceeded the permissible limit. The salinity of the water of the three areas differed significantly with the highest values in the coastal plain and decreasing salinity towards the plateau ($\chi^2 = 20.35$ df = 2, $p < 0.001$).

None of the nitrogen components (ammonia, nitrate and nitrite) differed between areas during the wet season ($\chi^2 < 5.84$ for all components, df = 2, $p > 0.05$). The concentration of ammonia varied from 0.16 to 12.25 mg l^{-1} in the coastal plain with a median of 0.40 mg l^{-1}, from 0.17 to 24.62 mg l^{-1} (median 0.49 mg l^{-1}) in the park and from 0.04 to 12.82 mg l^{-1} on the plateau (median 0.41 mg l^{-1}). The highest values were found in the wells of the coastal plain and the caves in the park. The nitrate content ranged from 0 to 134.65 mg l^{-1} in the coastal plain with a median of 8.7 mg l^{-1}. The highest concentrations were measured in wells, with 7 % of them (one out of 14) exceeding the permissible limit. The nitrate concentrations in the park varied from 0 to 5.40 mg l^{-1} (median = 0). All of the water points were within the permissible limit. On the plateau, the nitrate levels ranged from 0 to 74.05 mg l^{-1} with a median of 0 mg l^{-1}. Here, 15 % of the wells were outside the permissible limit. Nitrite concentrations in the coastal plain var-

Table 3 Median and range of the water parameters: EC, TDS, NH_4, NO_3, NO_2, PO_4, Fe

Area	Type	Season	EC (µS cm^{-1})	TDS (ppm)	NH_4 (mg l^{-1})	NO_3 (mg l^{-1})	NO_2 (mg l^{-1})	PO_4 (mg l^{-1})	Fe (mg l^{-1})
Coastal Plain Park	Well (wet: $N = 14$; dry: $N = 10$)	Wet	9,738	4,862	0.35	10.55	2.75	22.30	0.44
			1,595–5,4384	797–27,136	0.16–12.25	0–134.70	0–12.00	0.14–66.30	0–1.96
		Dry	8,966	4,498	0.82	9.31	0.13	4.48	0.64
			1,877–44,450	940–23,083	0.27–6.89	4.10–24.60	0.07–0.59	1.95–23.70	0.02–26.50
	UNICEF well ($N = 2$)	Wet	1,575 / 3,087	787 / 1,544	0.37 / 0.44	0.10 / 10.70	0.00 / 3.00	20.10 / 25.50	0.83 / 0.87
		Dry	1641 / 3,026	821 / 1,513	0.60 / 0.65	2.90 / 5.00	0.11 / 0.13	4.50 / 11.10	0 / 0.33
	Cave ($N = 1$)	Wet	1,157	579	0.40	0	0	21.25	0.73
		Dry	1,566	786	0.41	8.39	0.14	5.45	0.01
	Sinkhole ($N = 1$)	Wet	979	490	0.56	0	1.5	26.75	0.95
		Dry	1,450	725	1.94	0.58	0.15	49.97	1.50
Park	Cave ($N = 5$)	Wet	2,998	1,499	0.84	0.10	2.50	41.50	0.15
			1,051–3,121	533–1,560	0.17–24.62	0–3.40	2.00–3.00	28.00–42.20	0.04–0.64
		Dry	3,021	1,511	0.26	0.43	0.10	9.90	0.02
			1,488–3,048	744–1525	0.22–0.32	0–3.30	0.04–0.14	4.40–16.23	0–9.00
	Sinkhole ($N = 4$)	Wet	1,729	824	0.49	0	3.75	43.18	0.74
			1,505–3,008	666–1,503	0.26–0.78	0–5.4	0.50–10.00	26.70–53.20	0.13–1.32
		Dry	1,817	908	0.33	0.58	0.14	6.04	1.20
			1,566–3,021	783–1,514	0.24–0.95	0–2.00	0.03–0.76	2.10–32.83	0.01–4.50
	Spring ($N = 1$)	Wet	3,162	1,582	0.26	0	0.40	28.10	0.21
		Dry	3,177	1,591	0.34	1.03	1.00	52.00	7.50
Plateau	Well (wet: $N = 14$; dry: $N = 10$–11)	Wet	341	170	0.41	0	2.00	24.00	0.81
			13–2,475	17–1,239	0.04–12.82	0–74.10	0.01–15.01	9.40–50.85	0.16–2.23
		Dry	677	335	1.32	0.06	0.54	12.35	0.02
			108–2,695	53–1,348	0.07–5.46	0–19.20	0.18–2.73	1.95–45.55	0–1.20
Acceptable limit			2,000**	1,000**	17***	50*	0.2*	5**	0.3*

EC electric conductivity, *TDS* total dissolved solid, NH_4 ammonia, NO_3 nitrate, NO_2 nitrite, PO_4 phosphate, *Fe* Iron, *NS* no standard
* WHO (2011), ** Madagascar Code Eau (1999), *** EPA (2013a,b)

ied from 0 to 12.00 mg l^{-1} with a median of 1.76 mg l^{-1}; 71 % of the wells, the UNICEF well of Itampolo and the sinkhole exceeded the permissible limit. The highest concentrations were measured in the wells. In the park, the nitrite concentrations ranged from 0 to 10.00 mg l^{-1} (median = 0 mg l^{-1}). The sinkholes had the highest concentrations. Together with the caves, they exceeded the permissible limit. The nitrite concentrations on the plateau ranged from 0.01 to 15.01 mg l^{-1} with a median of 2.00 mg l^{-1}; 92 % of the samples exceeded the permissible limit.

In the coastal plain, the phosphate concentrations ranged from 0.1 to 66.30 mg l^{-1} (median = 22.70 mg l^{-1}) with the highest concentrations measured in the UNICEF well. The dissolved phosphate in the park varied from 26.7 to 53.20 mg l^{-1} (median = 40.23 mg l^{-1}). The phosphate concentrations on the plateau varied from 9.40 to 50.85 mg l^{-1} with a median of 40.23 mg l^{-1}. The permissible limit was surpassed in 93 % of the wells located in the coastal plain and in all of the other water samples. The phosphate concentrations differed significantly between water sources of the three areas ($\chi^2 = 9.86$, df = 2, $p < 0.01$).

In the coastal plain, the iron concentrations ranged from 0 to 1.96 mg l^{-1} (median = 0.78 mg l^{-1}) 64 % of the wells and all of the other water sources exceeded the permissible limit. The highest concentrations were registered in the UNICEF wells. The iron in the park water sources varied between 0.04 and 1.32 mg l^{-1} (median = 0.21 mg l^{-1}); 20 % of the caves and 50 % of the sinkholes exceeded the permissible limit. On the plateau, the iron concentration varied from 0.16 to 2.23 mg l^{-1} with a median of 0.81 mg l^{-1}; 86 % of the water sources exceeded the permissible limit. The iron content did not differ between water sources of the three areas ($\chi^2 = 3.90$, df = 2, $p > 0.05$).

Dry Season

The water temperature varied from 25.6 to 28.1 °C (mean ± standard deviation: 27.0 ± 0.8 °C) in the coastal plain, from 26.5 to 29.1 °C (28.1 ± 1.6 °C) in the national park and from 22.1 to 28.3 °C (24.8 ± 2.0 °C) on the plateau ($\chi^2 = 17.19$, df = 2, $p < 0.001$). The UNICEF well and the spring had the highest temperature in the coastal plain and the park, respectively.

The mean values of pH ranged from 6.7 to 7.7 in the coastal plain (7.2 ± 0.3), from 6.7 to 7.7 in the national park (7.1 ± 0.3) and from 6.9 to 7.8 on the plateau (7.3 ± 0.3), thus indicating neutral to slightly alkaline conditions during the dry season. The pH did differ significantly between areas ($\chi^2 = 15.87$, df = 2, $p < 0.001$). All of the samples were within the permissible limits of the various standards.

Across all three areas, the DO ranged from 1.7 to 12.9 mg l^{-1} with a median of 4.8 mg l^{-1}. The highest values of DO were found in the coastal plain UNICEF well and the spring in the park. The oxygen saturation ranged from 5.0 to 25.6 % with a median of 14.4 %. Neither DO nor oxygen saturation differed between areas ($\chi^2 < 1.2$, df = 2, $p > 0.05$).

Electrical conductivity in the coastal plain varied from 1,450 to 44,450 μS cm^{-1}; with a median of 7,332 μS cm^{-1}; 90 % of the wells and one of the two UNICEF wells exceeded the acceptable limit. The water can be described as unsuitable in wells, doubtful in UNICEF wells and permissible in sinkhole and caves. The EC ranged from 1,488 to 3,177 μS cm^{-1} in the park with a median of 2,456 μS cm^{-1}. The spring, 60 % of the caves and 25 % of the sinkholes exceeded the permissible limit. The water was doubtful in the sinkhole and the cave and unsuitable in the spring. On the plateau, the EC ranged from 108 to 2,695 μS cm^{-1} with a median of 673 μS cm^{-1} indicating good water quality; 9 % of the wells exceeded the permissible value. The difference between regions is highly significant ($\chi^2 = 23.90$ df = 2, $p < 0.001$).

In the coastal plain, the TDS varied from 725 to 23,083 ppm with a median of 3,665 ppm, 90 % of the wells and 50 % of the UNICEF wells exceeded the permissible limit. The sinkhole and the cave were non-saline, the UNICEF wells were slightly saline and the wells were moderately saline. Water was slightly saline in the park, with TDS values between 744 and 1,591 ppm and a median of 1,228 ppm. The spring, 60 % of the caves and 25 % of the sinkholes exceeded the permissible limit. The TDS on the plateau ranged from 53 to 1,348 ppm with a median of 335 ppm indicating non-saline water. 9 % of the wells exceeded the permissible limit. The difference between regions is highly significant ($\chi^2 = 23.95$, df = 2, $p < 0.001$).

Contrary to the wet season, all of the nitrogen components (ammonia, nitrate and nitrite) differed between areas during the dry season. Ammonia concentrations ranged from 0.27 to 6.89 mg l^{-1} in the coastal plain (median = 0.63 mg l^{-1}), from 0.22 to 0.95 mg l^{-1} (median = 1.32 mg l^{-1}) in the park and 0.07 to 5.46 mg l^{-1} (median = 1.32 mg l^{-1}) on the plateau. The highest concentrations were measured in the wells and the sinkhole. The difference between regions is significant ($\chi^2 = 11.07$, df = 2, $p < 0.01$). Nitrate concentrations ranged from 0.58 to 24.60 mg l^{-1} (median = 6.80 mg l^{-1}) in the coastal plain, from 0 to 3.25 mg l^{-1} (median = 0.58 mg l^{-1}) in the park and from 0 to 19.16 mg l^{-1} (median = 0.06 mg l^{-1}) on the plateau. All of the water samples were within the permissible limit. The difference between areas is highly significant ($\chi^2 = 17.40$, df = 2, $p < 0.001$).

In the coastal plain, the nitrite values varied from 0.07 to 0.59 mg l^{-1}, (median = 0.14 mg l^{-1}; 20 % of the wells; 50 % of the UNICEF wells exceeded the permissible limit. The highest concentration of nitrite was measured in the well. Nitrite concentrations ranged from 0.03 to 0.76 mg l^{-1}

(median = 0.13 mg l^{-1}) in the park; 50 % of the sinkholes and the spring exceeded the permissible value. The spring had the highest nitrite concentrations in the park. Nitrite concentrations were between 0.18 and 2.73 mg l^{-1} (median = 0.54 mg l^{-1}) on the plateau; 90 % of the water samples were outside the permissible limit. The difference between regions is highly significant ($\chi^2 = 14.65$, df = 2, $p = 0.001$).

In the coastal plain, the phosphate concentrations varied from 1.95 to 49.97 mg l^{-1}, (median = 4.93 mg l^{-1}); 40 % of the wells, one of the two UNICEF wells and all other water sources exceeded the permissible limit. The concentrations of phosphate in the park varied between 2.1 and 52.00 mg l^{-1} (median = 9.27 mg l^{-1}); the spring, the sinkholes and 80 % of the caves were above the limit. On the plateau, the phosphate concentrations ranged between 1.95 and 45.55 mg l^{-1}; with a median of 1.95 mg l^{-1}; 80 % of the wells were outside the permissible limit. The differences between regions are not significant ($\chi^2 = 1.90$, df = 2, $p > 0.05$).

In the water sources of the coastal plain, the iron concentration ranged from 0 to 26.50 mg l^{-1} (median = 0.30 mg l^{-1}). The highest concentrations were registered in the wells; 50 % of them exceeded the permissible limit. The iron concentration in the park ranged between 0 and 9.00 mg l^{-1} (median = 1.20 mg l^{-1}). The spring, 75 % of the sinkholes and 40 % of the caves were above the permissible limit. On the plateau, the iron concentration was between 0 and 1.20 mg l^{-1} (median = 0.02 mg l^{-1}); 20 % of the sampled water exceeded the permissible limit. These differences between areas are not significant ($\chi^2 = 4.64$, df = 2, $p > 0.05$).

Seasonal Variation of Physicochemical Parameters

In the coastal plain, temperature, pH, nitrite and phosphate concentrations were higher during the wet than during the dry season (Wilcoxon matched pairs signed ranks test: $p < 0.05$ for all comparisons). In the water sources of the national park, temperature, pH, nitrite and phosphate were higher during the wet than during the dry season, while DO, oxygen saturation, EC and the TDS were lower during the wet than during the dry season ($p < 0.05$ for all comparisons). On the plateau, temperature and iron concentrations were higher during the wet than during the dry season ($p < 0.05$ for both comparisons).

Microbiological Assessment

The percentages of the water sources contaminated by coliform, *E. coli*, *Salmonella* spp. and *Vibrio* spp. are presented in Table 4. The concentrations of all four types of bacteria were positively correlated in both seasons (Spearman rank correlations for all pairwise comparisons: $r_s > 0.544$, $p < 0.05$; Table 5).

Wet Season

In the coastal plain, the total coliform count ranged from 0 to more than 60,000 colonies/100 ml; one of the UNICEF wells (the well at Itampolo) and all of the other sources were contaminated. The wells had the highest counts. *E. coli* varied from 0 to 11,700/100 ml, 93 % of the wells and the UNICEF wells at Itampolo contaminated. The sinkhole and the cave were

Table 4 Percentage of water sources contaminated by bacteria

Area	Source	Season	Total coliform	*E. coli*	*Salmonella* spp.	*Vibrio* spp.
Coastal Plain	Well ($N = 14, 10$)	Wet	100	93	93	93
		Dry	100	90	100	100
	UNICEF well ($N = 2$)	Wet	50	50	50	50
		Dry	50	50	50	50
	Cave ($N = 1$)	Wet	0	0	100	100
		Dry	0	0	0	0
	Sinkhole ($N = 1$)	Wet	100	0	0	100
		Dry	100	100	0	100
Park	Cave ($N = 5$)	Wet	100	60	40	20
		Dry	100	60	40	60
	Sinkhole ($N = 4$)	Wet	100	0	50	0
		Dry	100	50	75	25
	Spring ($N = 1$)	Wet	100	100	100	100
		Dry	100	100	100	0
Plateau	Well ($N = 14, 11$)	Wet	100	64	86	79
		Dry	100	60	100	70

Table 5 Spearman rank correlations between physicochemical water characteristics and concentrations of different bacteria

	T (°C)	pH	DO (mg l^{-1})	O_2 (%)	EC (μS cm^{-1})	TDS (ppm)	NH_4	NO_3	NO_2	PO_4	Fe	*E. coli*	Total coliform	*Salmonella* spp.	*Vibrio* spp.
T (°C)		−0.213	0.329*	0.421**	0.081	0.081	−0.218	−0.234	−0.047	0.241	−0.334*	0.029	−0.307*	−0.249	−0.240
pH	−0.282		0.311*	0.259	0.265	0.282	0.173	0.245	−0.148	−0.001	0.093	0.146	0.147	0.273	0.182
DO (mg/l)	0.413*	−0.083		0.928**	0.023	0.031	−0.173	0.245	−0.152	0.077	0.093	−0.108	−0.152	−0.119	−0.231
O_2 (%)	0.381*	−0.080	0.902**		−0.083	−0.074	−0.232	0.161	−0.096	0.058	0.123	−0.051	−0.175	−0.192	−0.220
EC (μS cm^{-1})	0.350*	−0.339*	−0.106	−0.146		0.997**	−0.028	0.501**	0.073	−0.113	−0.268	0.530**	0.261	0.512**	0.373*
TDS (ppm)	0.353*	−0.346*	−0.106	−0.147	0.998**		−0.030	0.511**	0.084	−0.120	−0.271	0.534**	0.266	0.505**	0.376*
NH_4	−0.619**	−0.03	−0.192	−0.064	−0.031	−0.035		−0.049	−0.270	0.189	−0.210	0.076	0.306*	0.188	0.066
NO_3	0.047	−0.066	0.042	−0.060	0.626**	0.624**	0.214		−0.07	−0.114	0.139	0.283	0.302	0.283	0.320*
NO_2	−0.437**	0.115	−0.098	−0.04	−0.517**	−0.513**	0.447**	−0.224		−0.084	−0.112	0.016	−0.053	−0.047	0.012
PO_4	0.206	0.075	0.548**	0.500**	−0.362*	−0.357*	−0.306	−0.239	0.103		−0.135	−0.254	−0.283	−0.281	−0.475**
Fe	0.206	0.075	0.548**	0.500**	−0.362*	−0.357*	−0.306	0.100	−0.239	0.196		−0.135	−0.147	−0.113	−0.119
E. coli	−0.063	0.261	−0.083	−0.209	0.336	0.318	0.037	0.386*	−0.196	0.054	0.068		0.683**	0.730**	0.713**
Total coliform	−0.569**	0.407*	−0.354*	−0.325	−0.138	−0.146	0.300	−0.088	0.333	0.090	0.070	0.544**		0.727**	0.762**
Salmonella spp.	−0.386*	0.251	−0.393*	−0.453**	0.206	0.192	0.106	0.221	0.102	−0.015	0.207	0.680**	0.833**		0.728**
Vibrio spp.	−0.364*	0.258	−0.181	−0.322	0.130	0.120	0.209	0.251	0.017	0.054	0.044	0.797**	0.703**	0.675**	

Values are correlation coefficients. Values above the diagonal represent correlations for data from the wet season ($N = 41$ or 42). Values for the dry season are listed below the diagonal ($N = 34$ or 34)

* $p < 0.05$; ** $p < 0.01$

free of *E. coli*. *Salmonella* spp. ranged from 0 to 14,400/100 ml; 93 % of the wells and one of the two UNICEF wells were contaminated. The sinkhole was free of *Salmonella* spp. but the caves were contaminated. *Vibrio* spp. concentration varied from 0 to 6,700/100 ml; 93 % of the wells, the UNICEF well at Itampolo, the sinkhole and the cave were contaminated.

In the park, the total coliform varied from 300 to more than 60,000/100 ml, all of the water sources were more or less infested but the caves had the highest concentrations of coliforms. *E. coli* concentration varied from 0 to 30,200 ml^{-1}; the spring and 60 % of the caves were contaminated. *Salmonella* spp. concentrations varied from 0 to 6,600/100 ml; the spring, 50 % of the sinkholes and 40 % of the caves were infested. *Vibrio* spp. concentrations ranged from 0 to 7,600/100 ml; the spring and 20 % of the caves were infested.

On the plateau, the total coliform varied from 2,300 to more than 60,000/100 ml. All of the wells were infested. *E coli* were found in 64 % of the wells; their concentrations varied from 0 to 1,000/100 ml. *Salmonella* spp. concentrations varied from 0 to 8,100/100 ml; they were present in 86 % of the wells. *Vibrio* spp. concentrations ranged from 0 to 30,800/100 ml. They were present in 79 % of the wells.

Dry Season

In the coastal plain, the total coliform concentrations varied from 0 to more than 60,000/100 ml, one of the two UNICEF wells and all of the other water sources were contaminated. The wells had the highest values. The concentrations of *E. coli* ranged from 0 to 27,000/100 ml; 90 % of the wells, one of the two UNICEF wells and the sinkhole were infested. *Salmonella* spp. concentrations were varied from 0 to 27,000/100 ml; all of the wells and one of the two UNICEF wells were infested. *Vibrio* spp. concentrations varied from 0 to 14,100/100 ml, all of the wells, the sinkhole and one of the two UNICEF wells were infected.

In the park, the total coliform ranged between 200 to 5300/100 ml, all of the studied water sources were more of less infested; the spring had the highest value. *E. coli* concentrations varied from 0 to 4,100/100 ml. The spring, 60 % of the caves and 50 % of the sinkholes were infested. *Salmonella* spp. concentrations ranged from 0 to 800/100 ml, the spring, 75 % of the sinkholes and 40 % of the caves were infested. *Vibrio* spp. count varied from 0 to 800/100 ml 60 % of the caves and 25 % of the sinkholes were infested.

On the plateau, the total coliform varied between 41 to more than 60,000/100 ml. All of the samples were contaminated. *Escherichia coli* concentrations ranged from 0 to 1,500/100 ml. They were present in 60 % of the wells.

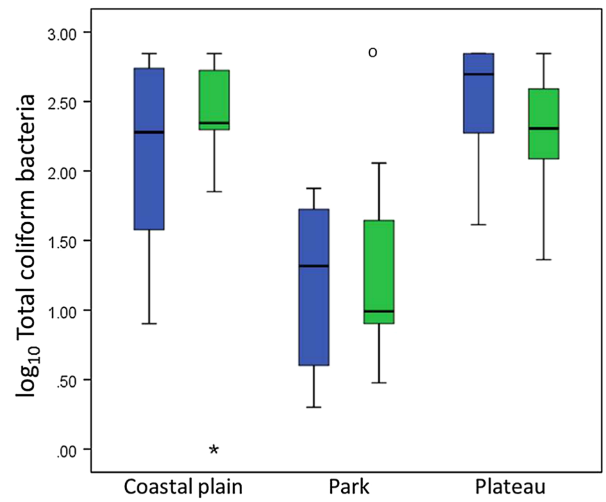

Fig. 3 Seasonal and spatial variation of infection intensity of different water bodies by "Total coliform bacteria"

Salmonella spp. were found in all of the studied wells, their concentrations ranged from 2 to 11,200/100 ml. *Vibrio* spp. were recorded in 70 % of the wells; their concentrations varied from 0 to 7,200/100 ml.

Seasonal and Spatial Variation in Microbial Contamination

The intensity of bacterial contaminations did not differ between seasons, neither in the total sample, nor within areas (Wilcoxon matched pairs signed ranks test: $p > 0.05$ for all comparisons).

Between areas the intensity of infection of the water bodies varied significantly for all groups of bacteria during both seasons, except for *E. coli* and *Salmonella* spp. during the dry season (Kruskal–Wallis analysis of variance: *E. coli* and *Salmonella* spp. dry season: $\chi^2 < 4.90$, df = 2, $p > 0.05$; for all other comparisons: $\chi^2 > 6.83$, df = 2, $p < 0.05$). Significance between areas is created mainly by the low bacterial concentrations in the park, as exemplified by the infection of total coliforms (Fig. 3).

Restricting the analyses of the intensity of bacterial infection to the wells of the coastal area and the plateau did not indicate any significant difference between the wells of the two areas with respect to total coliforms and *Vibrio* spp. in both seasons and for *Salmonella* spp. in the dry season (Mann–Whitney U Test: $z < 1.59$ for all comparisons, $p > 0.05$). *Salmonella* spp. concentrations were higher in the coastal area than on the plateau during the wet season ($z = 2.64$, $p < 0.01$) and for E. coli during both seasons (dry season: $z = 2.47$, $p < 0.05$; wet season: $z = 2.73$, $p < 0.01$).

Variation in Microbial Contamination Between Types of Water Sources

The analysis of possible effects of different structures to access water was hampered by the low sample size of structures other than wells, the absence of wells in the national park and the absence of any other water source but wells on the plateau. Therefore, the analysis had to be restricted to the coastal plain. Here, all but one of the open wells were contaminated by bacteria in both seasons. One of the UNICEF wells (at Itampolo) was also contaminated while the other (at Lavavolo) was not (Table 4).

Relations Between Microbial Contamination Intensity and Physicochemical Characteristics

During the wet season *E. coli*, *Salmonella* spp. and *Vibrio* spp. were positively correlated with the two measures reflecting salinity (EC and total dissolved solids; Spearman rank correlations: $r_s > 0.50$, $p < 0.05$; Table 5). This correlation was not apparent during the dry season. During the dry season, the intensities of some bacterial infections were correlated with temperature, pH, DO and oxygen saturation in a non-systematic way (Table 5).

Discussion

Diseases contracted through drinking water kill about 5 million children annually (WHO 2004). Many infectious diseases are transmitted by water through the faecal–oral route (Shittu et al. 2008) with diarrhoea being the most frequent. Globally, it constitutes the sixth largest cause of mortality (Montgomery and Elimelech 2007), caused mainly by the consumption of unsafe water. Safe drinking water, sanitation and good hygiene are fundamental to health, survival, growth and development (WHO and UNICEF 2006). However, in developing countries, these basic necessities are still lacking. Conditions are most severe in sub-Saharan Africa, where 42 % of the people are without safe water, 64 % do not have improved sanitation, and death rates due to diarrheal diseases are higher than in any other region of the world (Montgomery and Elimelech 2007). The rural areas of Madagascar are even below these African figures with only 35 and 26 % of the populations having access to such facilities (WHO and UNICEF 2006). Given the present poverty, the high human population growth and the scarcity of water, the Mahafaly Plateau of south-western Madagascar is one of the regions that require comprehensive management plans for sustainable land management (SuLaMa 2011). A better understanding of the water situation and the factors that might influence water quality is an essential component for management recommendations for the sake of the human population and conservation of a globally unique ecosystem (Olson and Dinerstein 1998; Guyot 2002; Fenn 2003; Rajaobelison et al. 2003; Kaufmann and Tsirahamba 2006; Scales 2011; Ferguson et al. 2013).

General Physicochemical Parameters

In the study area of south-western Madagascar, most of the water samples were not suitable for human consumption. Almost all of the parameters were above the permissible limits.

The water temperature in the study area is relatively high. The water temperature especially of the wells of the plateau was significantly higher during the wet than during the dry season. This is related to the seasonal variations of the air temperature with the minimum temperature in the dry season and maximum in the wet season (Ratovonamana et al. 2013). This indicates that the surface conditions have a noticeable impact on the water condition with no or a short time delay. There is no official standard in water temperature; however, the rise in water temperature accelerates chemical reactions, reduces solubility of gases, amplifies taste and odour and elevates metabolic activity of organisms (Usharani et al. 2010). While these processes are to be expected, the consequences of a two degree temperature difference were not reflected in the other chemical physicochemical components.

The pH affects the taste of water. A pH below 4.5 makes the water highly corrosive, with sour taste and the pH above 10 gives soapy taste to the water (WaterAid 2004). The pH of all water samples in the coastal plain, the national park and the plateau range between 6.71 and 8.09 and thus are within the WHO permissible limit of pH 6.5–8.5.

Dissolved oxygen values in natural waters vary according to the physicochemical and biological activities (Jameel and Sirajudeen 2006). There is no standard concerning DO. Nevertheless, higher oxygen concentrations are correlated with low pollution. The concentration of 5.0 mg l^{-1} is the minimum considered ideal for drinking water (Bhanja and Ajoy 2000). Dissolved oxygen and oxygen saturation were lower (in caves and sinkholes) in the wet season than in the dry season, due to the decline of the solubility of oxygen in water with increasing temperature (Lowe-McConnel 1987).

Electrical conductivity is a measure of the ability of water to conduct electrical current. It is a measure of salinity which is important for renal dis-function, greatly affects the taste and thus has a significant impact on the user acceptance of the water as potable (Pradeep 1998). The present study shows very high values of electrical conductivity in the coastal plain (979–54,384 μS cm^{-1}). The EC of the water in the northern part of the coastal plain were highest, with higher values than seawater ($EC = 52{,}000\ \mu S\ cm^{-1}$) in some sources. This observation is in agreement with the results of Guyot (2002) who reported that the northern part of the coastal plain has a significant marine influence while the southern part was less mineralized and is independent of the sea. The water in the caves and the sinkholes were less mineralized but still has relatively high electrical conductivity compared with other karst water ($EC > 2{,}000\,\mu S\ cm^{-1}$). The EC of the karst water north of the Onilahy is less than $1{,}000\,\mu S\ cm^{-1}$ (Guyot 2002). The water was slightly saline on the plateau, 14 % of the wells exceeded the permissible limit of EC and TDS. Because of the high concentration of NaCl and SO_4in the soil, some places in the Betioky region have salty water (WaterAid 2004). Two watering places namely, Andranomasy–Beomby and Andranomasy–Andremba had EC values above $2{,}000\,\mu S\ cm^{-1}$.

The high nitrogen content is an indicator of organic pollution. It results from the added nitrogenous fertilizers, decay of dead plants and animals, manures, wastewater disposal and from oxidation of nitrogenous waste products in human and animal excreta. The increase in one or all the above factors is responsible for the increase of nitrogen content (Abdel-Rahman 2002; Jameel and Sirajudeen 2006). Three forms of nitrogen namely ammonia (NH_4), nitrate (NO_3) and nitrite (NO_2) were assessed during this study. There is no standard for ammonia, but the EPA recommended criterion is 17 mg l^{-1} (EPA 2013a,b). Except for the cave of Andanoilove in the national park all other water sources were below this recommendation. Nitrate is found naturally in the environment (WHO 2011) and most of the sampled sources were within the permissible limit except some open water (7 and 15 % of the wells in the coastal plain and the plateau, respectively, and one of the sinkholes in the park). The nitrate contents were within the permissible limit during the dry season. During the wet season, the runoff seems to intensify leaching of nitrate from the surface. The open water sources have no protection against this phenomenon. The nitrite concentrations were above the permissible limit in most of the water sources, with the highest concentrations measured in wells, indicating sewage from water use.

The concentration of phosphate is high in the coastal plain, the park and the plateau. The concentrations in wells were significantly higher during the wet than in the dry season. The erosion and solution of phosphate from rocks in the study area seem to be the main origin of the phosphate. Rain dissolves the elements slowly and the runoff water carries the dissolved phosphate into the water source (EPA 2013a,b). The sewage from zebu dung and human excreta are likely to contribute most to this process.

Iron is an essential element for humans (Moore 1973). Although iron has little concern as a health hazard, it is still considered a nuisance in excessive quantities (WHO 2011). The number of source above the acceptable limit is more important during the wet season. Wells of the coastal plain had higher iron concentrations during the wet than during the dry season.

Microbial Assessment

None of the bacteria counts showed any significant seasonal difference. Coliforms are present in the environment naturally (EPA 2013a,b). The total coliform count for all samples, except for one UNICEF well and the cave in Lavavolo, were exceeding the standard for coliform bacteria in drinking water of zero total coliform per 100 ml of water (WaterAid 2011). This high coliform count may be an indication that the water sources are contaminated with faeces (EPA 2003). *E. coli* and other faecal coliforms are only from human and animal waste (EPA 2013a,b). Thus, faecal coliform indicates the presence of faecal material from warm blooded animals (Krishnan et al. 2007). Most of the water samples were positive for *E. coli*. *Escherichia coli* concentrations were high and mainly in wells. This is consistent with the extensive sampling of wells north of our study area where wells were highly contaminated with bacteria (Ramampiherika and Ravaloson 2010). This contamination is due to improper construction, shallowness, animal waste, proximity to toilets, sewage and various human activities around the well (Bitton 1994). No human activities are allowed inside the park. Nevertheless, some of the caves and the sinkhole contain small numbers of *E. coli*. Wild animals (e.g. bats, birds, tortoises, etc.) and livestock excreta constitute the most important source of contamination. The presence of an important quantity of bats guano in many caves also contributes to this situation.

Salmonella spp. (Enterobacteriaceae) are widely distributed in the environment, but some species or serovars show host specificity. Some species are restricted to humans (*S. typhi* and generally *S. paratyphi*), though livestock can occasionally be a source of *S. paratyphi*. A large number of serovars, including *S. typhimurium* and *S. enteritidis*, infect humans and also a wide range of animals, including poultry, cows, pigs, sheep, birds and even reptiles (WHO 2011). *Salmonella* are spread through animal and human faeces. Waste can enter the water through different ways including sewage and water runoff.

Vibrio spp. can persist in water. There are a number of pathogenic species but *Vibrio cholerae* is the only pathogenic species of significance from freshwater environments, though a number of different serotypes can cause diarrhoea (WHO 2011). Cholera is typically transmitted by the faecal—oral route, and the infection is predominantly achieved by the ingestion of water contaminated by faeces.

Conclusions and Consequences

In general, the region has poor water quality. The pH was suitable for domestic use even though the other physicochemical and bacterial parameters exceeded the limit defined by national and international standards frequently. The number of sources exceeding the standard limit is higher during the wet than during the dry season. The runoff combined with the water percolation transport sewage components into the source.

The coastal plain has the worst water quality, characterised by high salinity (high EC and TDS), nitrogen content and bacteria counts, indicating an important organic pollution. Lavavolo constitutes an exception, as the water in the UNICEF well and the cave of this village was potable. Most of the physicochemical parameters were within the permissible limit. *E. coli* and total coliforms were absent and *Salmonella* spp. and *Vibrio* spp. counts were very low. The sampled water on the plateau has a better quality. The EC and TDS were within the permissible limits, except for water sources of Andranomasy. However, the problem of nitrogen and bacterial pollution was still present.

The park is a protected area where local people do not have access except for some restricted activities. However, organic pollution was apparent in this area. Thus, the water contamination may have a non-human origin. The nitrogen and bacteria contaminations could be from the wild animal excreta (tortoises, bats, lemurs, birds, etc.). Livestock in the park contribute also to this phenomenon especially during the dry season when water and forage are scarce outside the park and animals use the forest intensively (Ratovonamana et al. 2013).

The water contamination in the villages located on the plateau and the coastal plain is primarily of anthropogenic origin. Sewages are essentially from the non-use of sanitation infrastructure, the multiple use of the source (for bathing, drinking, cleaning, cattle watering, etc.) and the lack of a water protection strategy. Simple behavioural changes of the human population could help to reduce contamination and thus improve the human health situation considerably.

The finding that activities on the surface have immediate impacts on the water quality has consequences not only for human health but also for the planning of future water use. So far, the aquifers used by people were assumed to represent water provided by rain falling inland and to a minor fraction, by local rainfall (Guyot 2002; Rajaobelison et al. 2003). Especially the seasonal changes in water temperature paint a different picture. The fairly stable water temperature in caves and sinkholes across seasons suggests a primarily subterranean origin of these water bodies. However, in the coastal plain and on the plateau, water temperature in wells differs by about 1 and 2.7 °C between the hot wet and dry cool season, respectively. This indicates that the wells in both areas are recharged by a substantial contribution of rainfall and surface water during the wet season. Given the much higher increase in water temperature, this contribution of surface water seems to be more pronounced on the plateau than in the coastal plain and thus is likely to limit further growth of the human population, their livestock and options for irrigation.

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